



Point-of-Load Converters: Space Qualification Issues

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ABSTRACT

Tests were performed on space-qualified, point-of-load (POL) regulators to evaluate potential performance and reliability issues in their space use. For fiscal year (FY) 2010, two models of POL regulators were tested—a radiation-hard, low-drop-out linear regulator used in multiple flight applications, and a radiation-hardened, variable-output, synchronous buck regulator, which is intended for future flight applications. Some tests were performed at the thermal military extremes and below. Measurements performed include efficiency, regulation, load transient response, synchronization, and turn-on tests.

1.0 INTRODUCTION

Point-of-load (POL) converters (also called regulators) can supply constant voltage to a load, almost independently of load currents. The utilization of POL converters in space and in personal computers for field-programmable functions is increasing. This is because in order to get faster speed, designs in power systems have lowered the voltages considerably.

Resistive losses (current times resistance [IR]) can be very large. These are considerable when using integrated circuits (ICs) that can draw several amperes. Just a few inches of copper will give considerable IR losses when the current (I) is large. Such losses could be acceptable with single computer chips; however, all these added IR drops will not work when trying to control two or more boards. To get around this problem, sometimes small converters are used right at the point of load (to minimize IR losses), so that it is possible to have as many regulators as chips or ICs needed in a given power application. The voltages from the spacecraft bus are 30 or 32 V, but some of these regulators have 1.5 V outputs. Linear low-drop-out (LDO) regulators need a power supply minimum of around 2 V to get 1.5 V out.

This proximity to the “point of load” is how POL converters can avoid losses in supply lines, offering design flexibility, small footprint, and potentially high performance densities in many types of power management, including spacecraft power distribution. Thus, information on their reliability for space applications is very important, but not always readily available from manufacturers, since tests under high-reliability space conditions are often left to the users.

Some deviations from “ideal” behavior can be problematic in devices with a small output voltage. While a voltage ripple of 20 mV or even 50 mV is acceptable on a 15 V output regulator, for example, this size current “ripple” becomes too large of a percentage when the output voltage is on the order of 1.5 V. Voltage ripples tend to be small, and are a small fraction of the output voltage for most DC/DC converters. However, for POL regulators, these values can be a substantial percentage of their much smaller output voltages. For example, if a voltage ripple is measured to be 150 mV for a 1.5 V output regulator, this is 10% of the nominal output value, which might be unacceptable.

For linear regulators, the current drawn is equal to the current output, so the efficiency is defined as $V_{\text{out}}/V_{\text{in}}$ and is independent of load. Ideally, the input voltage should be close to the output voltage, and most LDO regulators are chosen this way. If it is not, then the efficiency drops and the regulator heats considerably. While these can be issues, sometimes LDO regulators are still the best solution for small loads. This is because they do not carry all the peripheral circuitry that is normally used in switching converters, so at small voltages and small loads they can still be an acceptable option.

Another issue with linear regulators is a potentially poor radiation tolerance, which is usually total dose related. The one device of this type used here (from MSKennedy) is marketed as “radiation tolerant,” and has been tested for a total dose up to 450 Krad.

Better overall radiation tolerance and also better efficiency is found in what are called “buck” switching regulators. These voltage regulators have a switch, an inductor, and a diode as their main components. They do have higher efficiency; however, when the voltages are low, a large portion of its power is consumed by the diode. This is why linear regulators are often chosen for low voltage and low load needs. Recently, the switching regulators have been cleverly redesigned [1–3] and use metal-oxide-semiconductor field-effect transistors (MOSFETs) and

clever timing for the lower voltage applications. These are often called “synchronous buck regulators.”

2.0 EXPERIMENTAL DETAILS

2.1 POL Regulators Tested

In the selection process of POL regulators used in this study, several factors were considered. One consideration was to test a cross section of the regulators offered by various vendors, so more than one vendor would be represented. Another consideration was to test regulators that are used in flight applications, or intended for near future flight applications. Testing regulators that use different architectures (or circuit design) was also one of the aims of this study.

A thorough search of the Jet Propulsion Laboratory's (JPL's) failure analysis log database for the last 12 years of failure analysis logs (from 1997 to present) shows frequent space flight use of devices from MSKennedy (MSK), International Rectifier (IR), Intersil, National Semiconductor, Linear Tech, and IR/Omnirel. This list is by no means exhaustive, and other manufacturers have provided parts for POL applications. Aeroflex and Intersil make POL regulator devices that are presently being considered for space applications as well.

A POL radiation-hardened, synchronous buck regulator device (the ISL70001SRH) was selected outside of this database since it became commercially available at the very beginning of the timeline for this work. Since this device is intended for space flight use, testing with the aim of identifying potential space qualifications issues was carried out. These included testing below the -55°C specified military range for this device, so that flight projects would have this data available to consider during the part selection process in environments that could potentially operate the device below -55°C .

Other types of tests, designed to simulate use in flight or space applications are being formulated and planned for fiscal year (FY) 2011.

Figure 2.1-1 shows the ISL70001 with the manufacturer-supplied application board. This regulator has been found (by the vendor) to be radiation hard to at least 100 KRad(Si) (total dose). Testing for single-event effects (SEEs) hardness shows it to be tolerant to at least 86.4 MeV/mg/cm^2 . This regulator has a fixed 1 MHz operating frequency, operates at input voltages of 3 V and 5.5 V, and has adjustable voltage output ranging from 0.8 V to 85% of the input voltage.

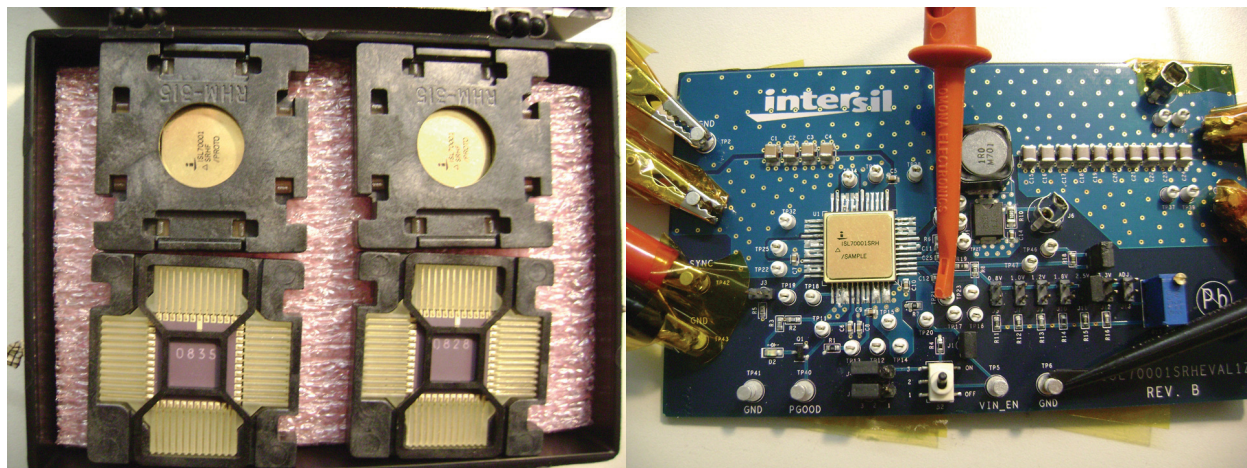


Figure 2.1-1. Optical photographs of ISL70001 buck regulator. Front and back of devices in ESD safe box are shown on the left, regulator mounted on manufacturer supplied application board is shown on the right.

While switching regulators provides regulation at a higher efficiency, and have less known radiation issues, there is still a need and place for LDO regulators in space applications. This is seen in the use of LDO linear regulators in several recent flight uses, including Mars Science Laboratory (MSL). The performance of LDO regulators is acceptable for low loads, and remains a good choice in applications where the extra circuitry of buck regulators would make them less effective for small loads. This is why LDO regulators are used in a multitude of flight applications, and are likely to be used for years to come.

The MSK5810RH was chosen since a version of this regulator is used extensively in different flight missions. Figure 2.1-2 shows the MSK5810RH LDO linear regulator. This is an adjustable output dropout positive linear regulator that has been shown to be radiation tolerant to 450 KRad(Si). It can deliver up to 5 amps output current and an output voltage that can be adjusted from 1.5 V to 7 V. Similar regulators are used extensively in MSL flight applications.

In addition to these two devices (the buck regulator and the LDO regulator), there are several converters that are available for testing and are commercial plastic-encapsulated microcircuits (PEMs). These are available for tests in FY11. Despite the fact that some of these devices are plastic and intended for commercial use, some of these tests would allow monitoring of their performance under some flight applications (they are being used in a multitude of non-critical flight applications). Determining their limitations in space use would enable flight insertion of these regulators at significant cost savings.

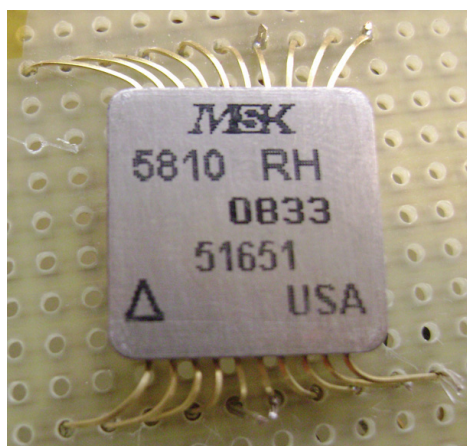


Figure 2.1-2. Photograph of the MSK5810RH linear regulator inserted in board. The application board was made per the instructions and diagram provided by the datasheet for this device. The surface shown with markings was pressed against the heat sink, and the thermocouple was placed between the two surfaces.

2.2 Temperature Control and Monitoring

POL regulators were tested at room temperature using a finned heat sink. The heat sink was also used for low temperature testing.

A small fan was also used to lower the temperature when the regulators were fully powered up. Thermocouples were T-type. They were mounted on thermal tape between the heat sink and the regulators with a plate bolted on the regulators to make good thermal contact. Figure 2.2-1 shows pictures of this set-up inside the thermal chamber used.

When tests are performed at temperatures other than room temperature (-40°C , -55°C , below -55°C , $+85^{\circ}\text{C}$, and at 125°C), a Sigma Systems M30 computer controllable thermal chamber is

used. The system's testing capabilities include both cycling and static temperature testing at extreme temperatures from -150°C to 250°C . With small thermal masses, the chamber achieved a ramp rate between temperatures above $10^{\circ}\text{C}/\text{min}$. Inert atmosphere testing was achieved through a built-in gas purge (using nitrogen). Adjustable, fail-safe, over-temperature and under-temperature protection was built into the system and is active in both manual operation and remote operation. The test chamber is 33 cm (L) \times 25 cm (W) \times 33 cm (H) and has eight 7.6 cm \times 1.3 cm door feed troughs and one 5 cm side port. Figure 2.2-1 shows the chamber both closed and with a regulator on a heat sink inside ready for tests.

Manual control was used in these tests for greater temperature accuracy. A thermocouple was placed very close to the converter devices; this is the reading that was used, rather than the chamber thermocouple reading. At full load, there was sometimes a small discrepancy, so the chamber temperature was adjusted accordingly.



Figure 2.2-1. Thermal chamber used in all DC/DC converter tests at -55°C (and below) and 125°C . Tests were also performed at room temperature before closing the chamber and bringing it to temperature to ensure measurements were as expected.

2.3 Test Equipment Used

- HP 6060B 3-60V and 0-60A-300W electronic load(s)
- HP 6654A DC power supply
- Temperature controller (data acquisition switch unit) Agilent 34970A
- FLUKE 77 Series II multi-meter (only for monitoring)
- Agilent 34401A digital multi-meter (for measurements)
- Switch (mercury) and small power supplies as needed for switch (only for turn-on tests)
- Pulse generator: HP 8112A (only for synchronization tests)
- Oscilloscope: Tektronix TDS 3014B (for start up, synchronization, and load transient response tests)
- Precision resistors (as needed)
- Capacitor boards (101 uFarad chip capacitors) and electrolytic capacitors as needed
- Heat sinks and thermocouple (to regulate and monitor temperature)
- Agilent 4395A network/spectrum/impedance analyzer and/or Ridley frequency analyzer (for stability margins tests)
- Thermal chamber to perform measurements at -55°C and at 125°C
- Current probe: Tektronix (AM 503 current probe amplifier)

2.4 Tests Being Performed

The following tests are being performed on selected POL regulators:

- Load regulation
- Efficiency
- Load transient response
- Synchronization
- Turn-on
- Stability margins (only on converters with sense pins) (to be done in FY11)
- Overload current and short circuit current power consumption and recovery voltage/time (to be done in FY11)
- Above tests performed at -55°C (or -40°C)
- Above tests performed below -55°C
- Above tests performed at 125°C (or 85°C) (FY11)
- Further tests to be performed in 2011
 - Infrared imaging (to determine junction temperature and to find hot spots in performing failure analysis)
 - Performance under dynamic loading

2.4.1 Efficiency and Regulation

Efficiency of a converter is defined as:

$$\% \text{ efficiency} = 100 * (\text{Power out}/\text{Power in}).$$

Regulation is defined as:

$$\% \text{ regulation} = 100 * (V_{\text{out any load}} - V_{\text{out nominal}})/(V_{\text{out nominal}}).$$

A slightly different definition for voltage regulation is used in some of the device datasheets. Therefore, to avoid confusion, the voltage regulation is given as a straight voltage value in the figures presented in this report. Figure 2.4-1 illustrates the set-up for these measurements

2.4.2 Load Transient Response

This test measures the converter's response to a transient load. When the load value is abruptly changed, the regulator's output shows a small voltage overshoot, which recovers to the steady state value after a short time. Maximum voltage overshoot and recovery times are given in the regulator's datasheets. Test results include values for voltage overshoot and recovery times, but this test can also uncover instabilities in the regulator operation, giving a qualitative indication of its feedback circuitry's performance. If the results indicate potential instabilities, then stability margin measurements tests would be appropriate (if feasible). Figure 2.4-2 illustrates the test set-up diagram to evaluate a regulator's response to a transient load.

The test was configured by connecting the output to an oscilloscope. If the device has more than one output, both outputs will have a small voltage overshoot even if only one output is pulsed. The tests were done at the different resistance loads described previously.

The electronic load (this test used HP 6060B) was programmed so that loads could be pulsed. Measurements of voltage overshoot and recovery times were then acquired from these scope traces.

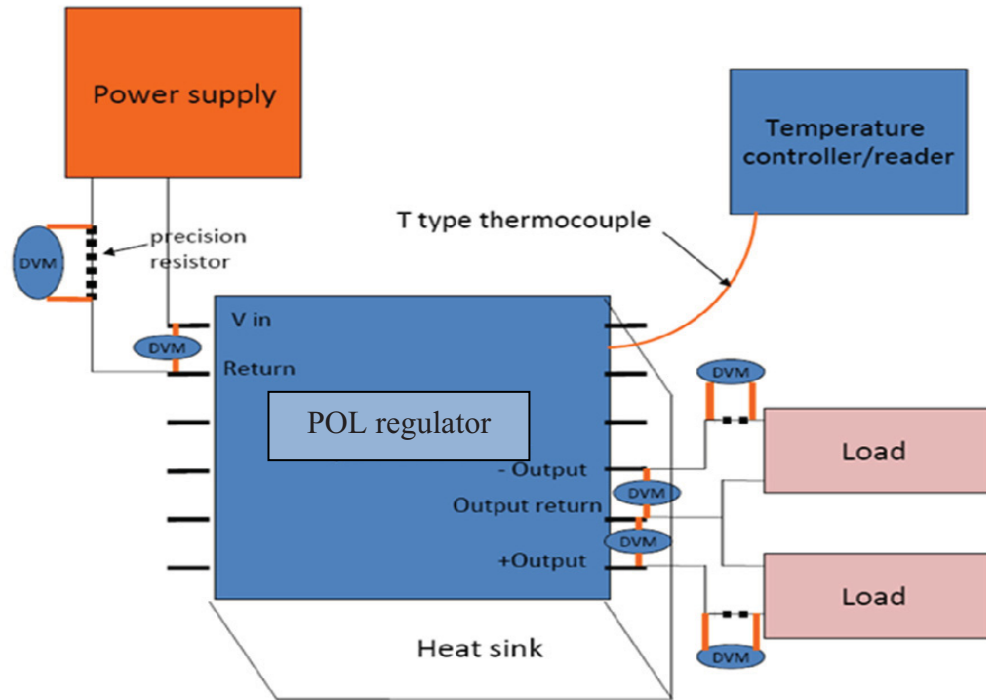


Figure 2.4-1. Set-up diagram for efficiency and voltage regulation measurements. Wire lengths were 2–3 feet; gauges were 18 or 22 feet for smaller signals.

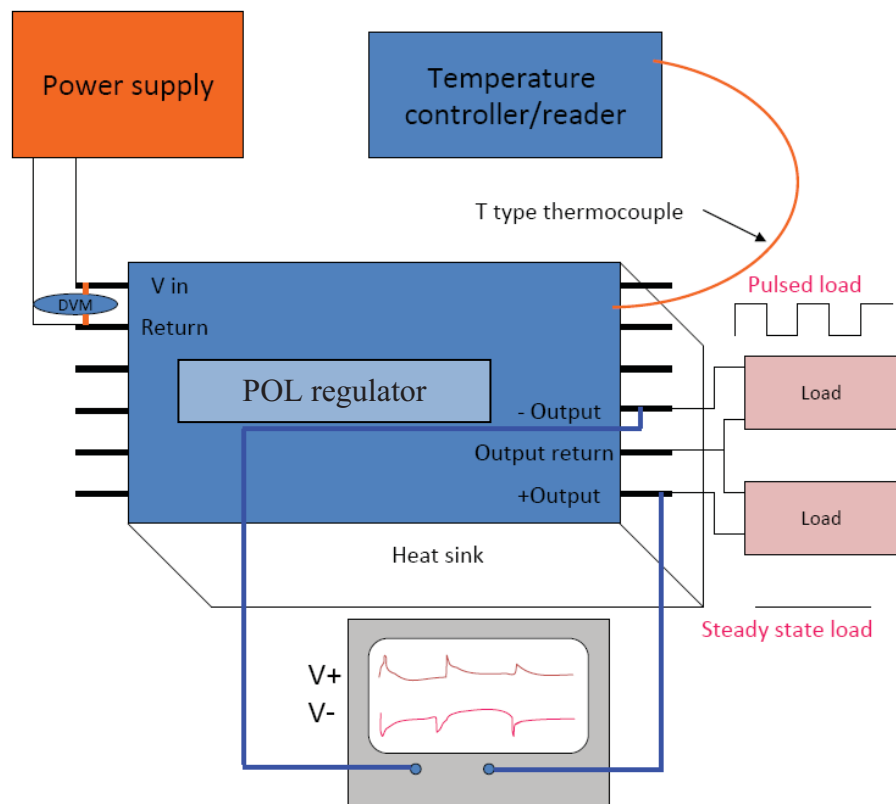


Figure 2.4-2. Test set-up diagram for the load transient response measurements.

2.4.3 Synchronization

This test verifies that the output voltage is synchronized with a pulse of a certain frequency (per vendor datasheet) when the unit locks to an external synchronization signal.

To perform the test, the output of a pulse generator is connected to the synch signal input pin. The outputs are monitored on an oscilloscope, and the waveform and the converter's output are recorded. Traces from the pulse generator waveform and both outputs are collected for each voltage input, load, frequency, and signal amplitude tested.

Figure 2.4-3 shows the test configuration for synchronization.

Since the linear regulator (MSK2810RH) does not have a synch function, synch was tested only on the ISL70001 device.

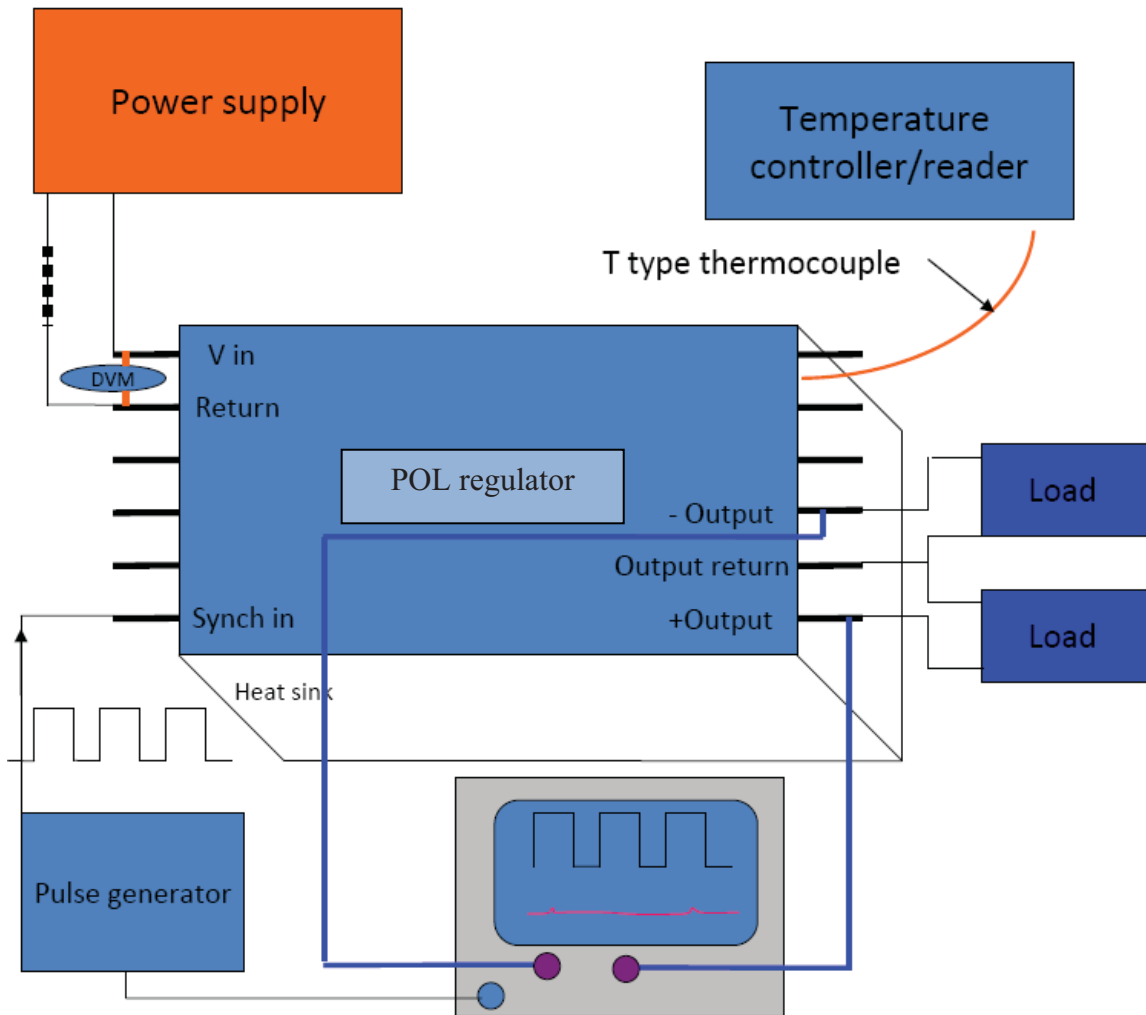


Figure 2.4-3. This test verifies that the output voltage is synchronized with an external pulse of a certain frequency. Synchronization for the ISL70001 is 1 MHz, with 20% allowed variation, so measurements were made from 800 KHz to 1.2 MHz (per vendor datasheets).

2.4.4 Turn-on

Figure 2.4-4 shows a diagram for these tests. Turn-on can encompass four different tests:

1. The first test has the power source on with the regulator first inhibited and then uninhibited. This is done for minimum, nominal, and maximum input voltages. Of course, this test is only possible for regulators that have a disable or inhibit function.
2. The second test applies the input voltage to the converter using a switch. Either an FET or a mercury switch may be used. Since Hg switches are permitted at the JPL, Hg switches were used when bounceless switches were required. Input power (voltage) and the converter output(s) are recorded on an oscilloscope simultaneously. These measure the delay time to achieve full regulation as well as any voltage overshoots.
3. The third test is similar to the second test but uses an input switch circuit that has a few milliseconds delay ramp. Vendor datasheets do not specify this test condition, and reconciling test methods/flight applications/vendor datasheets is still in progress.
4. The fourth test is to determine at what voltage the regulator starts to run. A voltage ramp is required and needs to be slow enough to determine when the converter starts. This particular test was done manually, since the turn-on is too slow to be captured on an oscilloscope. After ramp-up and turn-on, the input voltage to the converter is ramped down and the voltage at which the converter turns off is noted. This test, by its nature, can only be done near the minimum voltage, and it is done at both full load and minimum load. Minimum load was arbitrarily chosen as 10% for the tests shown here.

The second version of this test (listed above as 2), was the main turn-on test performed on the POL regulators. The inhibit release (version 1) was also tested on the ISL70001.

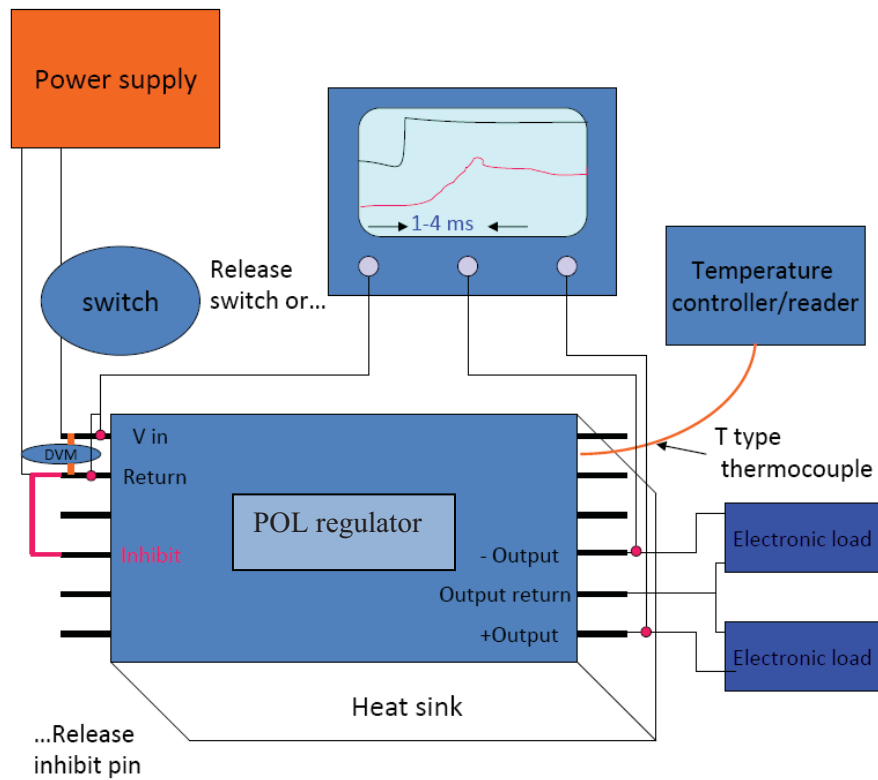


Figure 2.4-4. Set-up diagram for turn-on tests.

2.4.5 Stability Margins

Unless it is replaced with other tests, this test will be performed in FY11 on the ISL70001 since it is the only regulator tested that has a sense pin.

To perform this test, the regulator is connected as shown in Figure 2.4-5. This measurement can be done using a Ridley network analyzer as well as an Agilent network analyzer. In tests performed in FY07, measurements done on the ARH2812S showed that results obtained with both instruments were in agreement, except where the converter operated in the discontinuous mode (below 18% load for the ARH2812S) or when the input radio frequency (RF) signal was too large [4].

As the test set-up diagram for measuring gain and phase margins shows in Figure 2.4-5, an RF signal of an appropriate magnitude is sent out of a network analyzer or similar instrument. After an isolation transformer, the signal is connected to either side of a small resistor (about 100 ohms), placed between the sense positive line and the positive output. Signals B and A are monitored on both sides of such a resistor as illustrated in the figure. The magnitude, phase, and frequency of the RF signal from both A and B are monitored and compared. Phase changes and magnitude changes are recorded as a function of frequency. To establish the gain margins, the gain is read at the frequency at which phase margins are zero. To read the phase margins, phase is read at the frequency at which gain is one (or zero if using dB). These are expected to roughly follow design guidelines (at least 10 dB gain and 45-degree phase margins) throughout the range of load percentages and input voltages used and at room temperature as well as temperature extremes (-55°C and 125°C).

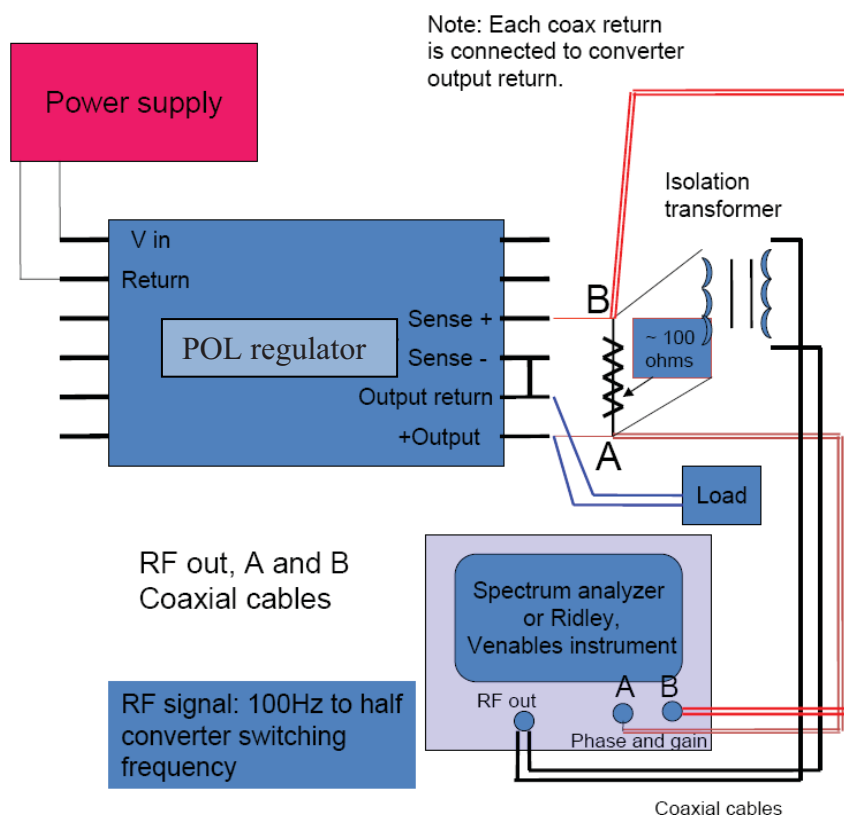


Figure 2.4-5. Set-up diagram for stability margins (open loop gain) measurements.

2.4.6 Power Consumption with Overload Current and Short-Circuit Recovery

This test is illustrated in Figure 2.4-6. In dual output models, overload current consists of setting one output to 50% load and the other output to 200% load. The objective of the test is to confirm that the converter goes into the “overload” trip mode. This happens when the emergency feedback loop detects a set current higher than a predetermined amount (pre-set by the manufacturers). Short-circuit test (or short-circuit power consumption) is done by setting one output to 50% and shorting the other output. This is done using a switch in between the two outputs and recording the traces on a scope. The POL regulators used in this study are both single output models. The MSK5810RH has an over current latch-off/latch pin that presumably provides short circuit protection. The ISL70001SRH has built in thresholds for both under voltage and over current.

Overload current and short circuit recovery performed in FY08 on DC/DC converters indicated this test to be destructive [5] if performed at the high end of the military thermal range (125°C). Since failures have also been encountered at room temperature, this test is considered to be potentially destructive. Therefore, these tests are to be performed last (at any temperatures), and after data is obtained from all other measurements, due to danger of converter or regulator failure.

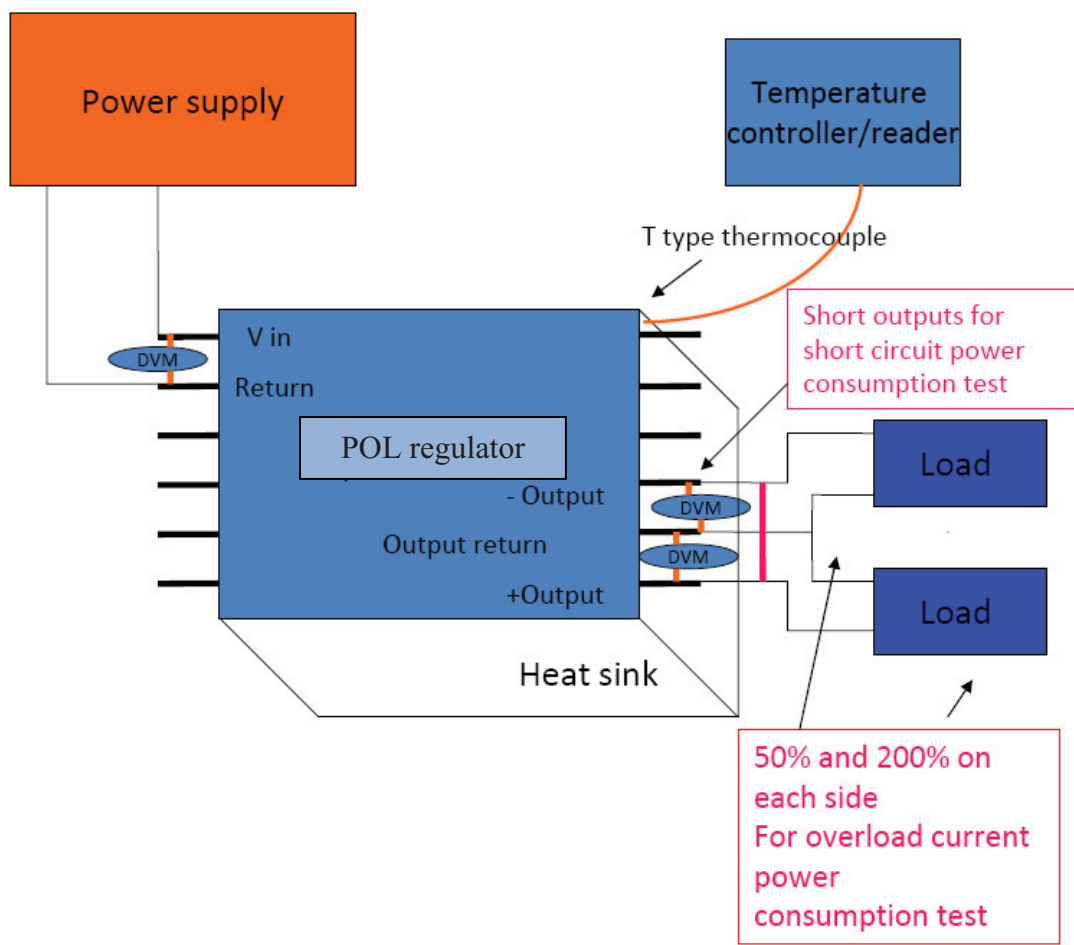


Figure 2.4-6. Set-up diagram for short-circuit and current overload tests.

2.4.7 Voltage Ripple and Noise

Voltage ripple is what is measured on an oscilloscope during steady state operation. This ripple has the switching frequency of the converter or regulator, and can be triangular shaped or sinusoidal. This voltage ripple is also the oscillation which increased in amplitude with decreasing temperature in converters tested in FY09 [6]. During that previous work, it was observed that the amplitude of such oscillation increased as the converter's operating temperature was decreased, due to the increase in effective series resistance of the output capacitors.

Output ripple and noise specifications describe the alternating current (AC) contamination riding on the direct current (DC) output of switching DC/DC converters or POL regulators. This AC signal usually consists of a periodic "low frequency" component derived from the basic switching frequency of the power converter and numerous, high-frequency "noise" components emanating from the high-speed edges and pulses within the converter. These phenomena might be observed over any bandwidth; however, they are traditionally specified over a bandwidth of 20 MHz.

The procedure for the measurement consists of setting the input voltage and output current to V_{in} (nominal) and I_{out} (maximum), respectively. The output ripple and noise voltage V_r is specified and measured in millivolts as either the peak-to-peak or RMS value of the AC component of the output voltage with both the input voltage and output current held constant.

2.4.8 Further Tests (to be Performed in 2011)

1. *Infrared imaging and microscopy.* Infrared (IR) imaging after turn-on (while connected) will be performed for comparison of heating spots. IR imaging will be done with two objectives:
 - To accurately determine the junction temperature during operating temperatures
 - To use IR imaging in failure analysis in the event one or more regulators fails (comparing operating and malfunctioning regulators to image the area that gets hotter first)
2. *Performance under dynamic loading.* This series of tests will involve monitoring the regulator's response under dynamic load (using dynamic input, besides dynamic loading for output).

3.0 RESULTS DISCUSSION

3.1 Efficiency and Regulation (at Room Temperature and -55°C).

Figures 3.1-1 and 3.1-2 show the measured efficiency vs. load for the ISL70001. Figure 3.1-1 shows results for 5 V input and 3.5 V output while Figure 3.1-2 shows results from the same measurements for 3.3 V input and 2.5 V output. In both graphs, measurements are shown for room temperature (25°C), 0°C , and -55°C . As can be seen in both graphs, the efficiency has a much stronger dependence on load value than on measurement temperature. Both Figures 3.1-1 and 3.1-2 also show that while the efficiency drops at low loads, this is still $\sim 50\%$ for a load as small as 5% of the maximum load. In fact with efficiencies as high as 80% and 90% with a 20% load, this regulator gets much better small load efficiencies than previous converters tested in FY07–FY09 [1–3], where efficiencies at 20% load were seen to drop as low as 40%.

Figure 3.1-3 shows the voltage regulation for ISL70001 regulator at room temperature. The data is shown as a function of load for two values of output voltage: 0.8 V and 2.5 V outputs. The input voltage was 3.3 V in both cases. The plot shows a decrease in the output voltage value as the load increases, and it can be seen that this decrease is proportionally more pronounced at the larger value of output voltage.

Figure 3.1-4 shows some temperature dependence of the voltage regulation for the same device. In this case, the input voltage is 5 V and the nominal output is 3.3 V. Just as in the efficiency curves, we see that the load value has a much greater effect on voltage regulation than temperature, at least in between -55°C and 25°C .

Figure 3.1-5 shows results from measuring output current and efficiency as a function of input voltage for a fixed output of 1.7 V in the MSK5810RH. This plot shows one of the issues with linear regulators. Since the input current is equal to the output current, good efficiencies can only be obtained at the larger values of input voltages.

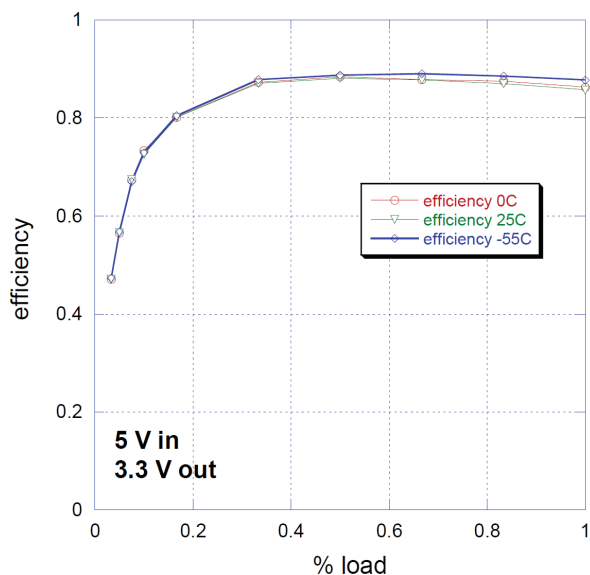


Figure 3.1-1. Efficiency vs. load for ISL70001 POL regulator measured at room temperature, 0°C and -55°C for 5 V input and 3.3 V output.

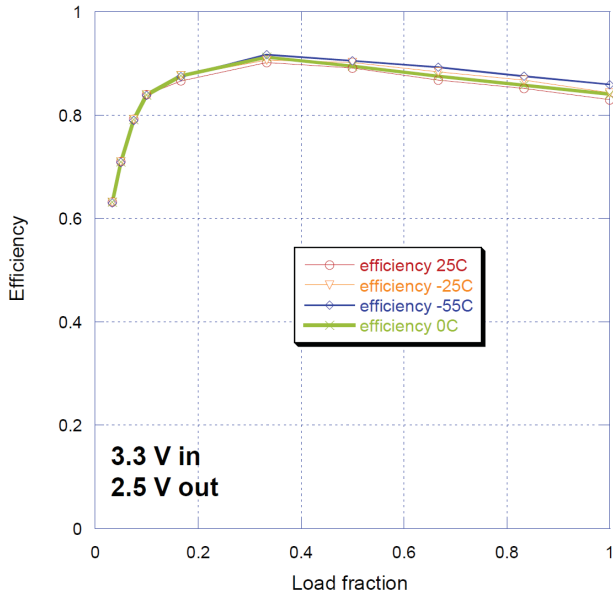


Figure 3.1-2. Efficiency vs. load for ISL70001 POL regulator measured at room temperature, 0°C and -55°C for 3.3 V input and 2.5 V output.

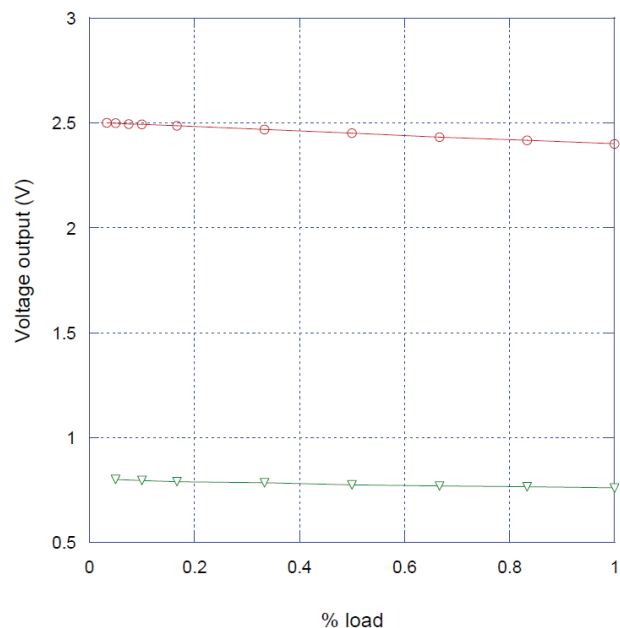


Figure 3.1-3. Voltage regulation for ISL70001 regulator at room temperature shown as a function of load for nominal 0.8 V and 2.5 V outputs.

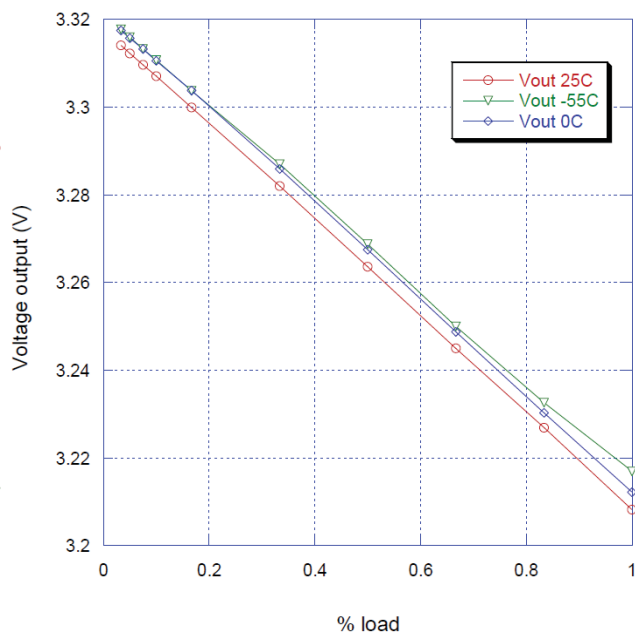


Figure 3.1-4. Output voltage as a function of load and temperature for the ISL70001 regulator, using 5 V input.

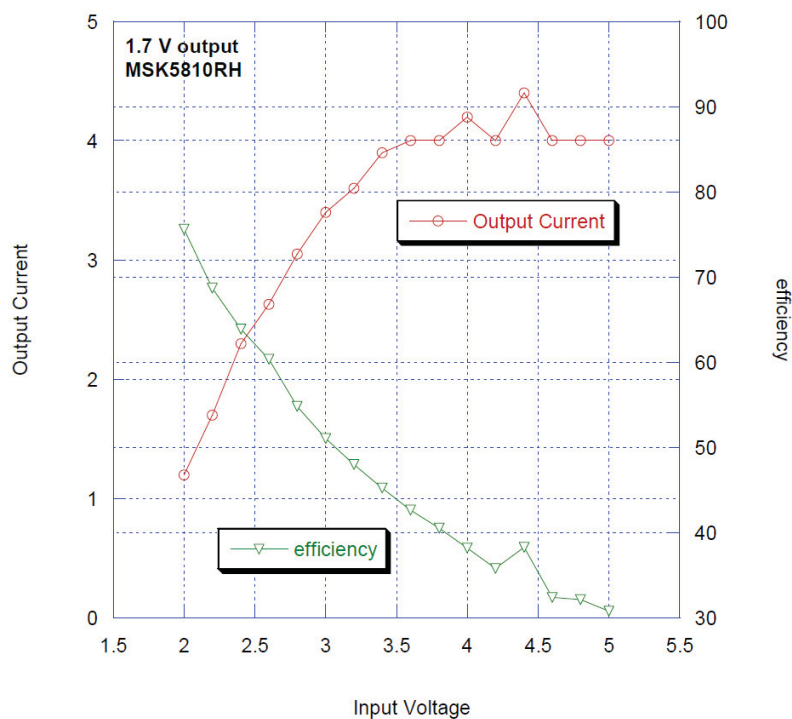


Figure 3.1-5. Output current and efficiency as a function of input voltage for MSK5810RH POL regulator. The output is somewhat flexible, and was adjusted to be 1.7 V out by adjusting the resistance value for R1 in the application circuit.

3.2 Load Transient Response (at 25°C and -55°C)

Load transient response measurements were made for both the linear and the buck regulator, at different temperatures.

Figures 3.2-1 and 3.2-2 show results from load transient response measurements on the buck regulator (ISL70001) at room temperature, and -55°C for a load step of 50% to 100% load, which in this case corresponds to 3 A to 6 A. As can be seen from these plots, the load transient responses at room temperature and -55°C are virtually indistinguishable.

Figures 3.2-3 and 3.2-4 show the same measurements but using a much smaller starting load, with a load step 10% to 50% (in this case, 0.3 A to 3 A). As can be seen, there is very little, if any, effect of temperature on the load transient response of this buck regulator between the thermal range between -55°C to 25°C. This is the case for standard or small step loads, as can be seen in Figures 3.2-1 to 3.2-4.

Figure 3.2-5 and 3.2-6 show the results of this measurement for the MSK2810RH at room temperature. In the first case (Figure 3.2-5), the load step was chosen to be from 40% to 80% load; in the second measurement, the load step was from 4% to 40% load (from 0.2 A to 2 A). The measurements starting from the very small load shows a small duration voltage undershoot, where the output voltage is momentarily less than 1.1 V. Percentage wise 1.1 V to the nominal 1.7 V represents a substantial discrepancy, so this result should be noted in intended linear regulator applications.

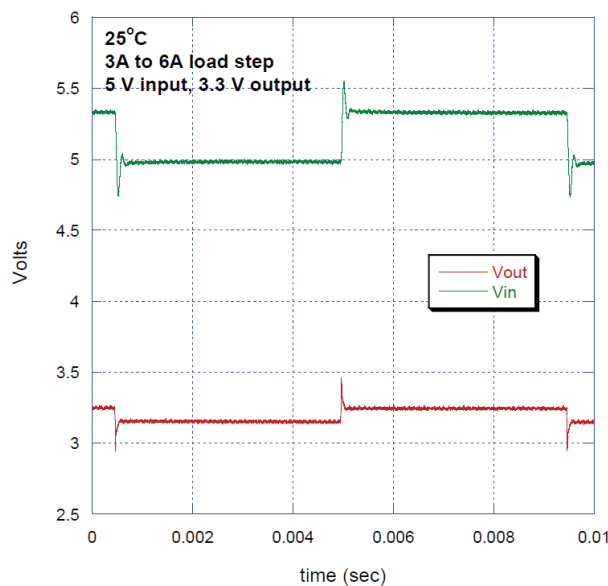


Figure 3.2-1. Load transient response test at room temperature for the buck regulator ISL70001. The load step was from 50% to 100% load, in this case from 3 A to 6 A. The input voltage was 5 V and the output was 3.3 V.

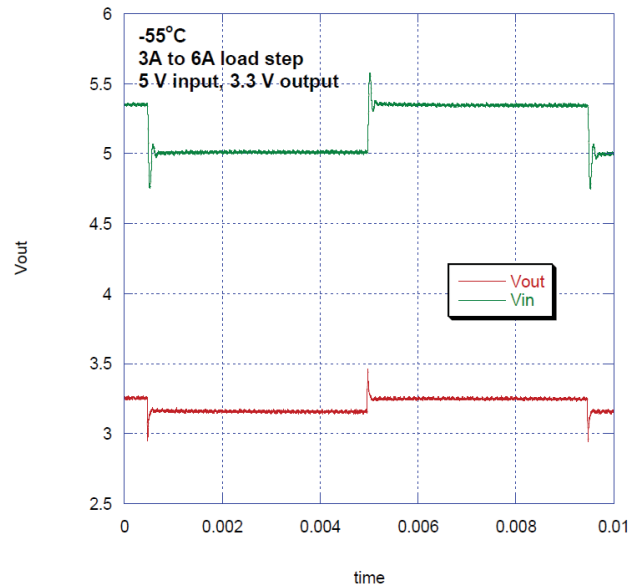


Figure 3.2-2. Load transient response test at -55°C for the buck regulator ISL70001. The load step was from 50% to 100% load, in this case from 3 A to 6 A. The input voltage was 5 V and the output was 3.3 V.

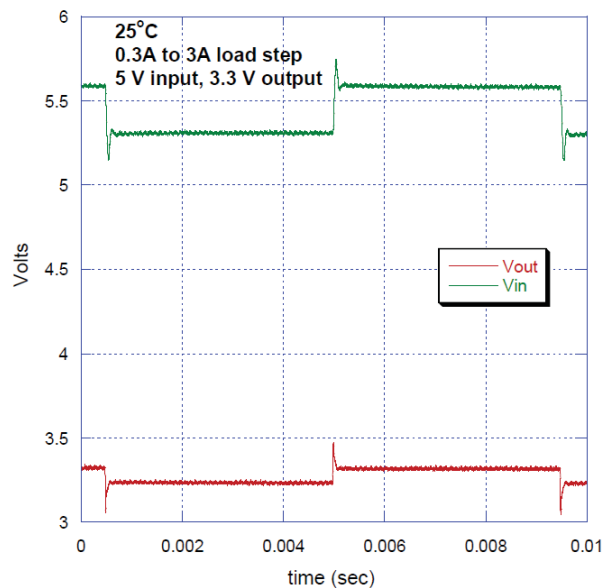


Figure 3.2-3. Load transient response test at room temperature for the buck regulator ISL70001. The load step was from 10% to 50% load, in this case from 0.3 A to 3 A. The input voltage was 5 V and the output was 3.3 V.

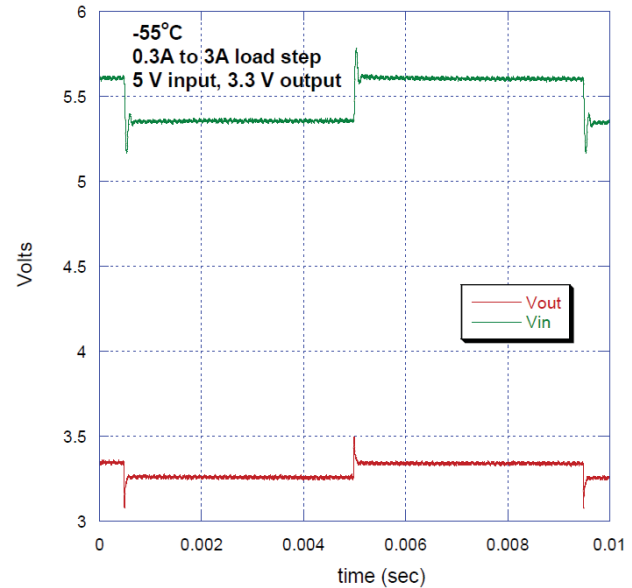


Figure 3.2-4. Load transient response test at -55°C for the buck regulator ISL70001. The load step was from 10% to 50% load, in this case from 0.3 A to 3 A. The input voltage was 5 V and the output was 3.3 V.

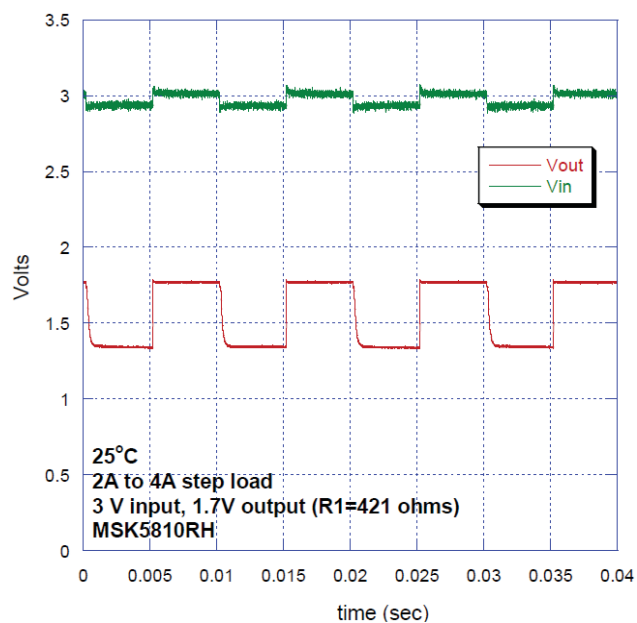


Figure 3.2-5. Load transient response test at 25°C for the linear regulator MSK5810RH. The load step was from 40% to 80% load, in this case from 2 A to 4 A. The input voltage was 3 V and the output was 1.7 V.

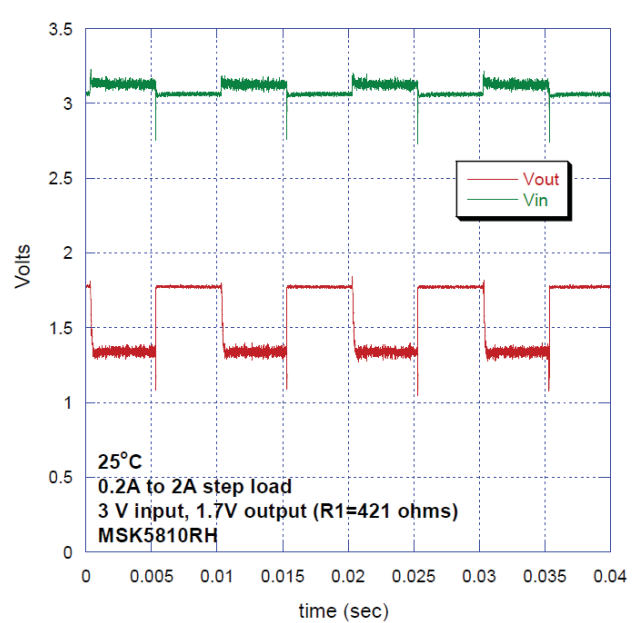


Figure 3.2-6. Load transient response test at 25°C for the linear regulator MSK5810RH. The load step was from 4% to 40% load, in this case from 0.2 A to 2 A. The input voltage was 3 V and the output was 1.7 V.

3.3 Synchronization

The linear regulator device tested has no synch function, but the buck regulator (ISL70001) can be connected with other regulators as a slave or master with a frequency of 1 MHz. The specifications state that it will synchronize within 20% (+ or –) of 1 MHz. This was verified at room temperature. A synchronization trace showing the input square wave from the pulse generator and the resulting 1 MHz ripple on the voltage output of the ISL70001 is shown in Figure 3.3-1.

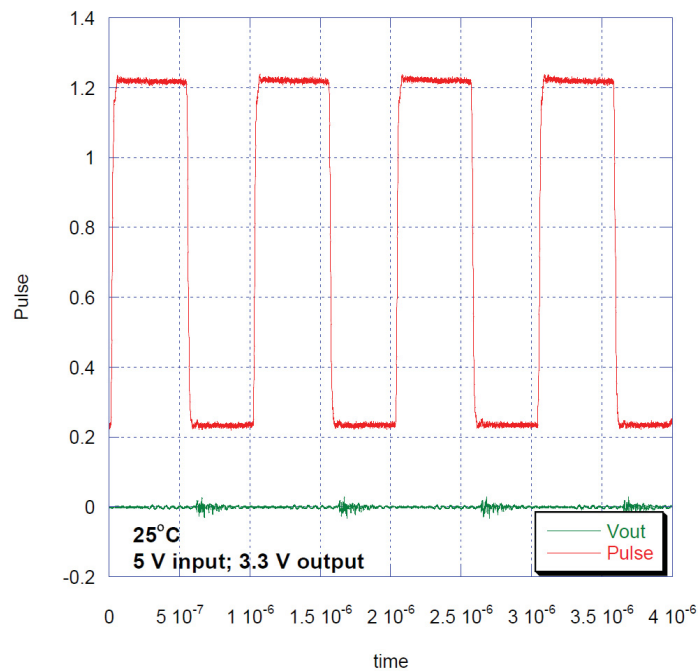


Figure 3.3-1. Synchronization plot for the ISL70001SRH using a pulse generator at 1 MHz. 5 V was the input and 3.3 V the output.

3.4 Turn-on

Turn-on tests at room temperature were carried out for both the MSK2810RH and the ISL70001SRH. Results from these tests are presented in the next few figures.

Figures 3.4-1 through 3.4-5 show results from the inhibit release type of turn on tests for the ISL70001SRH. These were measured for 0.3 amp, 0.6 amp, 1 amp, 3 amps, and 6 amps load, respectively.

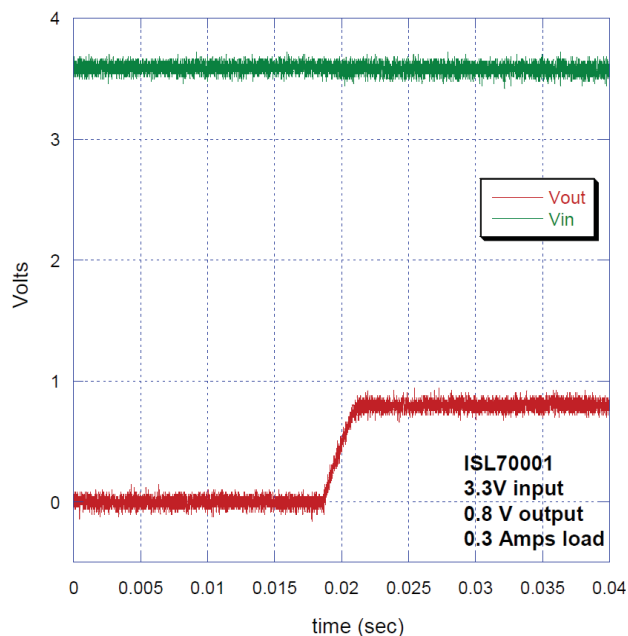


Figure 3.4-1. Turn-on measurement for the ISL70001SRH regulator by using the inhibit release option. 3.3 V input, 0.8 V output and 0.3 amp load were the test conditions.

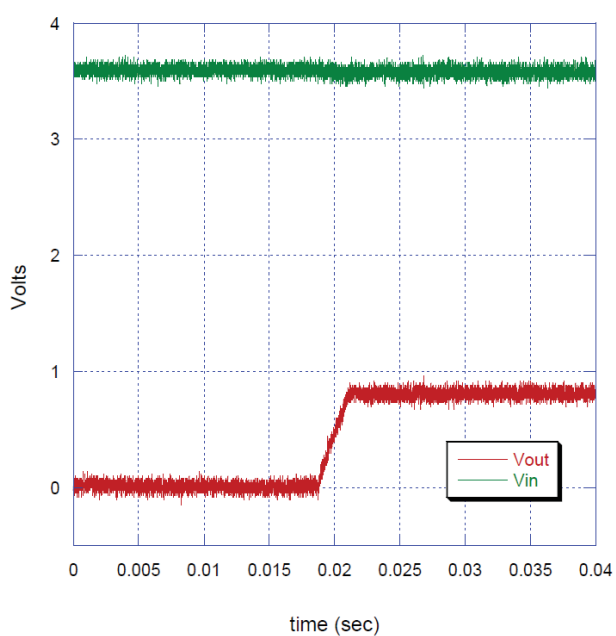


Figure 3.4-2. Turn-on measurement for the ISL70001SRH regulator by using the inhibit release option. 3.3 V input, 0.8 V output and 0.6 amp load were the test conditions.

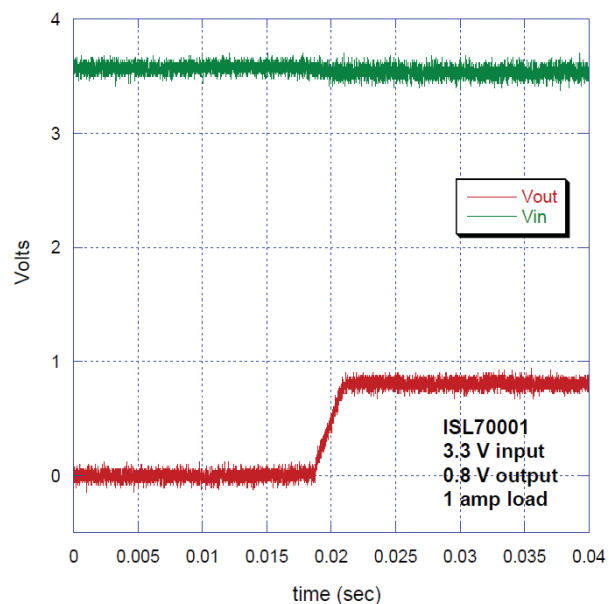


Figure 3.4-3. Turn-on measurement for the ISL70001SRH regulator by using the inhibit release option. 3.3 V input, 0.8 V output and 1 amp load were the test conditions.

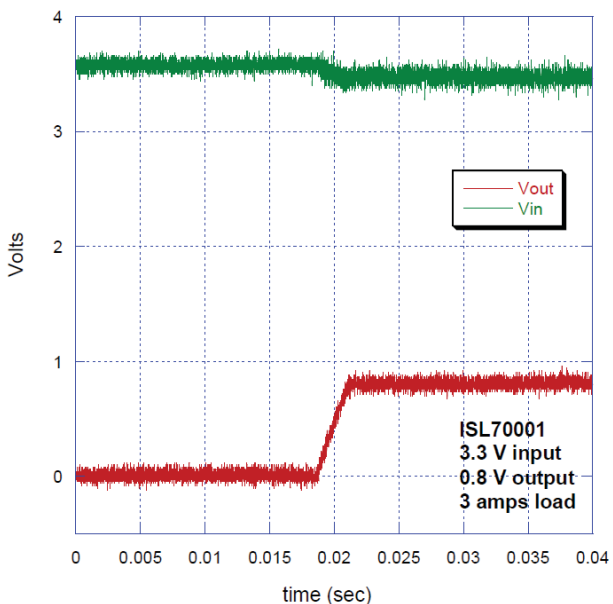


Figure 3.4-4. Turn-on measurement for the ISL70001SRH regulator by using the inhibit release option. 3.3 V input, 0.8 V output, and 3 amp load were the test conditions.

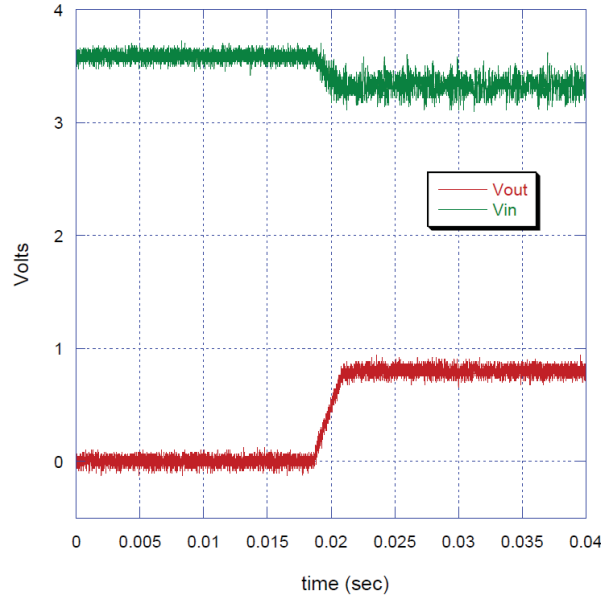


Figure 3.4-5. Turn-on measurement for the ISL70001SRH regulator by using the inhibit release option. 3.3 V input, 0.8 V output, and 6 amp load were the test conditions.

Figures 3.4-6 and 3.4-7 show results from the abruptly switched type of turn-on test. This was achieved using a Hg switch. Results are shown for 0.8 output voltage using 0.3 amp and 0.6 amp loads.

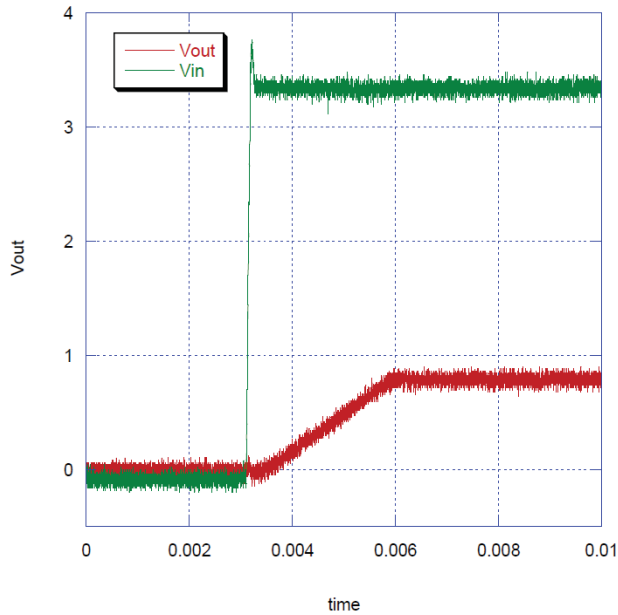


Figure 3.4-6. Hg switch turn-on measurement at room temperature for the ISL70001SRH regulator using 3.3 V input and 0.8 V output. The load was set at 0.3 amp.

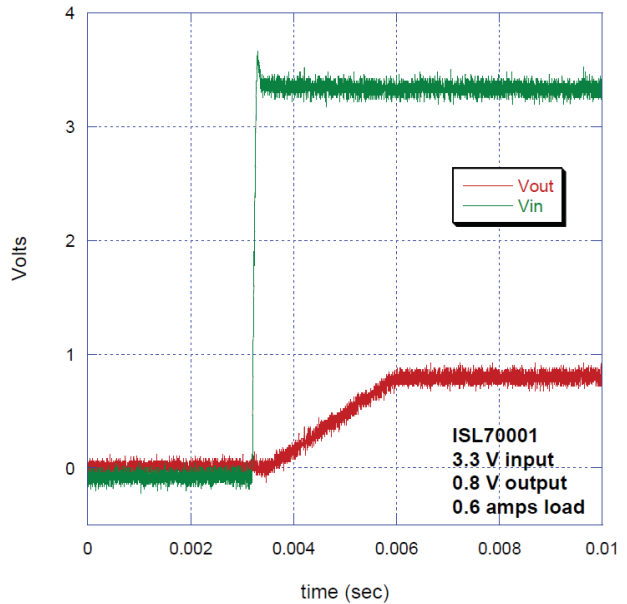


Figure 3.4-7. Hg switch turn-on measurement at room temperature for the ISL70001SRH regulator using 3.3 V input and 0.8 V output. The load was set at 0.6 amp.

Figures 3.4-8 to 3.4-11 also show results from turn-on tests using the Hg switch. For this test, 3.3 V input and 2.5 V output were used; using loads of 0.6 amp, 3 amps, 5 amps, and 6 amps, respectively. Figures 3.4-12 to 3.4-14 show results for turn-on tests for the linear regulator (MSK5810RH). Measurement conditions were 3 V input and 1.7 V output using 3 amps, 2 amps and 0.3 amp, respectively. As seen in Figure 3.4-14, the noise increases greatly at a load of 0.3 amp in this regulator. This increased noise was further investigated in the voltage ripple and noise measurements that follow.

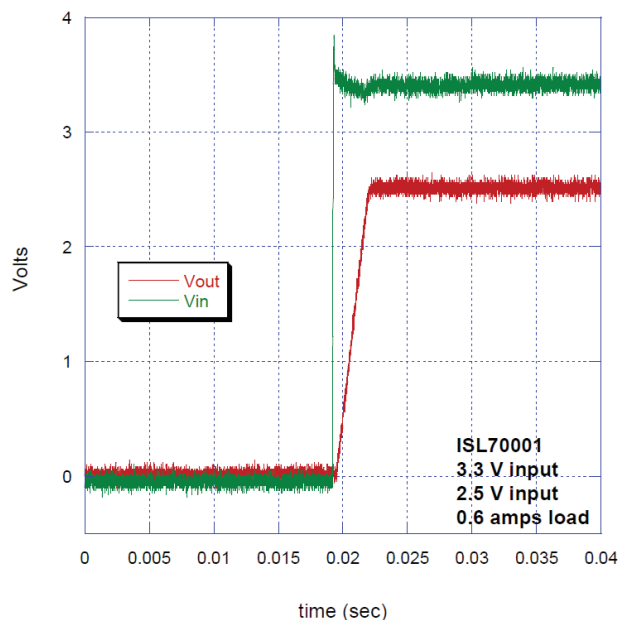


Figure 3.4-8. Room temperature turn on measurement for the ISL70001SRH regulator by using a Hg switch. 3.3 V input, 2.5 V output, and 0.6 amp load were the test conditions.

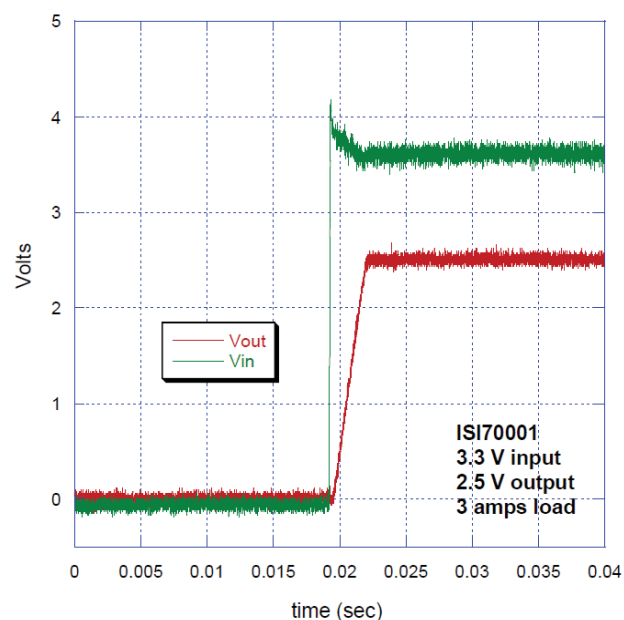


Figure 3.4-9. Room temperature turn on measurement for the ISL70001SRH regulator by using a Hg switch. 3.3 V input, 2.5 V output, and 3 amp load were the test conditions.

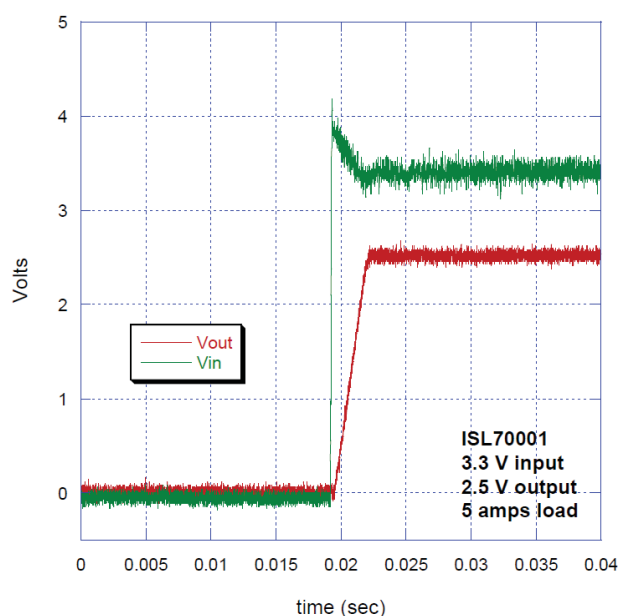


Figure 3.4-10. Room temperature turn on measurement for the ISL70001SRH regulator by using a Hg switch. 3.3 V input, 2.5 V output, and 5 amp load were the test conditions.

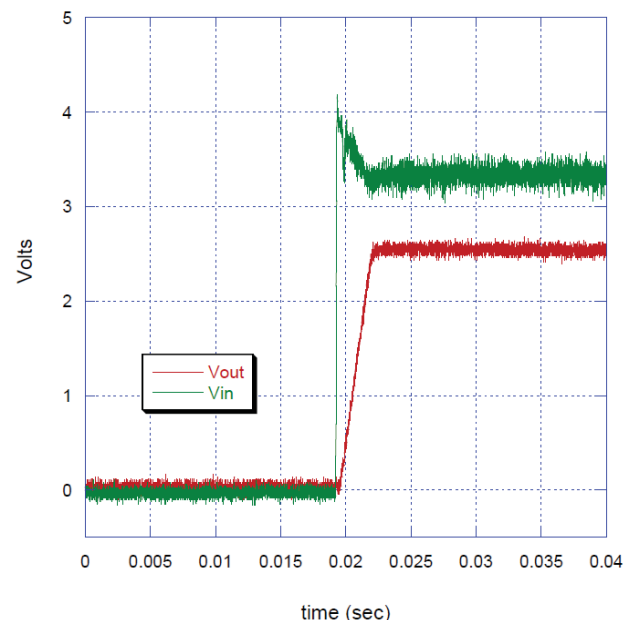


Figure 3.4-11. Room temperature turn on measurement for the ISL70001SRH regulator by using a Hg switch. 3.3 V input, 2.5 V output, and 6 amp load were the test conditions.

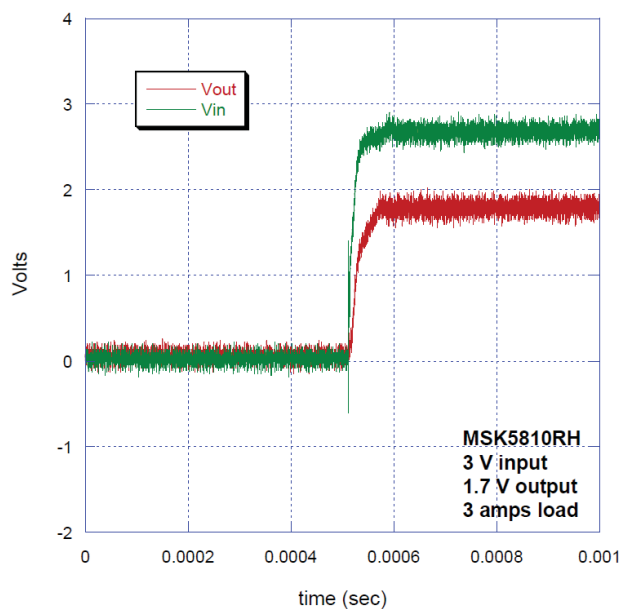


Figure 3.4-12. Turn-on measurement for the MSK5810RH regulator by using a Hg switch. 3 V input, 1.7 V output, and 3 amp load were the test conditions.

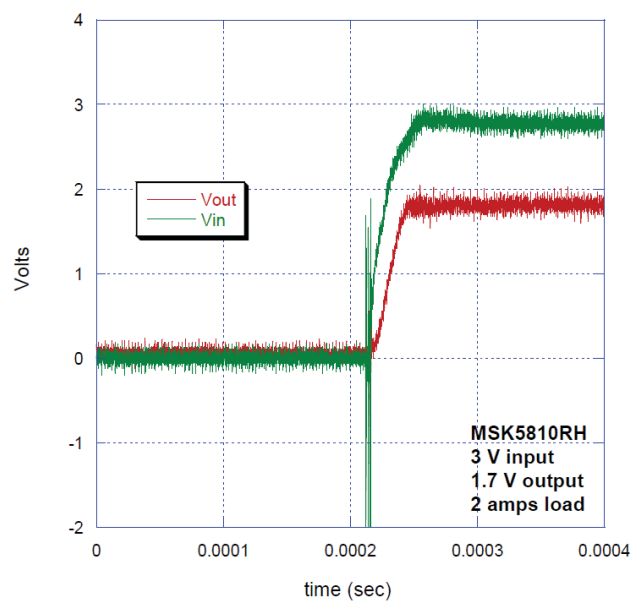


Figure 3.4-13. Turn-on measurement for the MSK5810RH regulator by using a Hg switch. 3 V input, 1.7 V output, and 2 amp load were the test conditions.

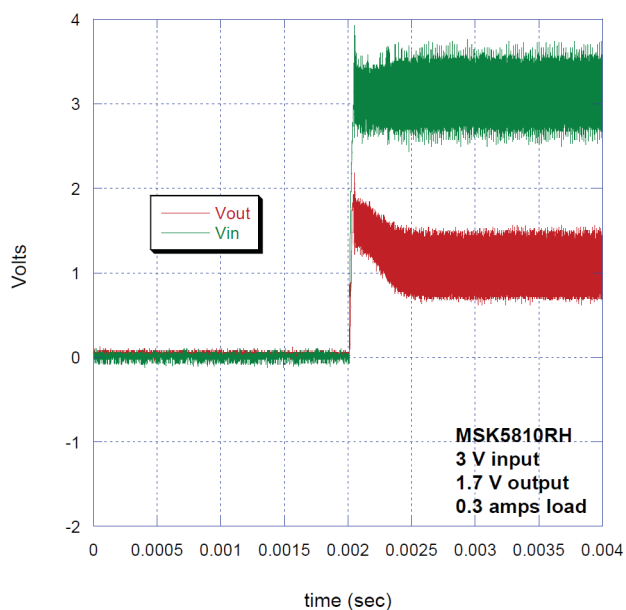


Figure 3.4-14. Room temperature turn-on measurement for the MSK5810RH regulator by using a Hg switch. 3 V input, 1.7 V output, and 0.3 amp load were the test conditions.

3.5 Voltage Ripple and Noise

Voltage ripple and noise was measured up to 20 MHz at room temperature for the MSK45810RH. Figures 3.5-1 to 3.5-4 show the results of these measurements for 2.5 V input and 1.5 V output and using different loads. The traces shown in the figures show the AC component of the output voltage starting from a very small load (0.01 amp), to near the maximum load of 3 amps.

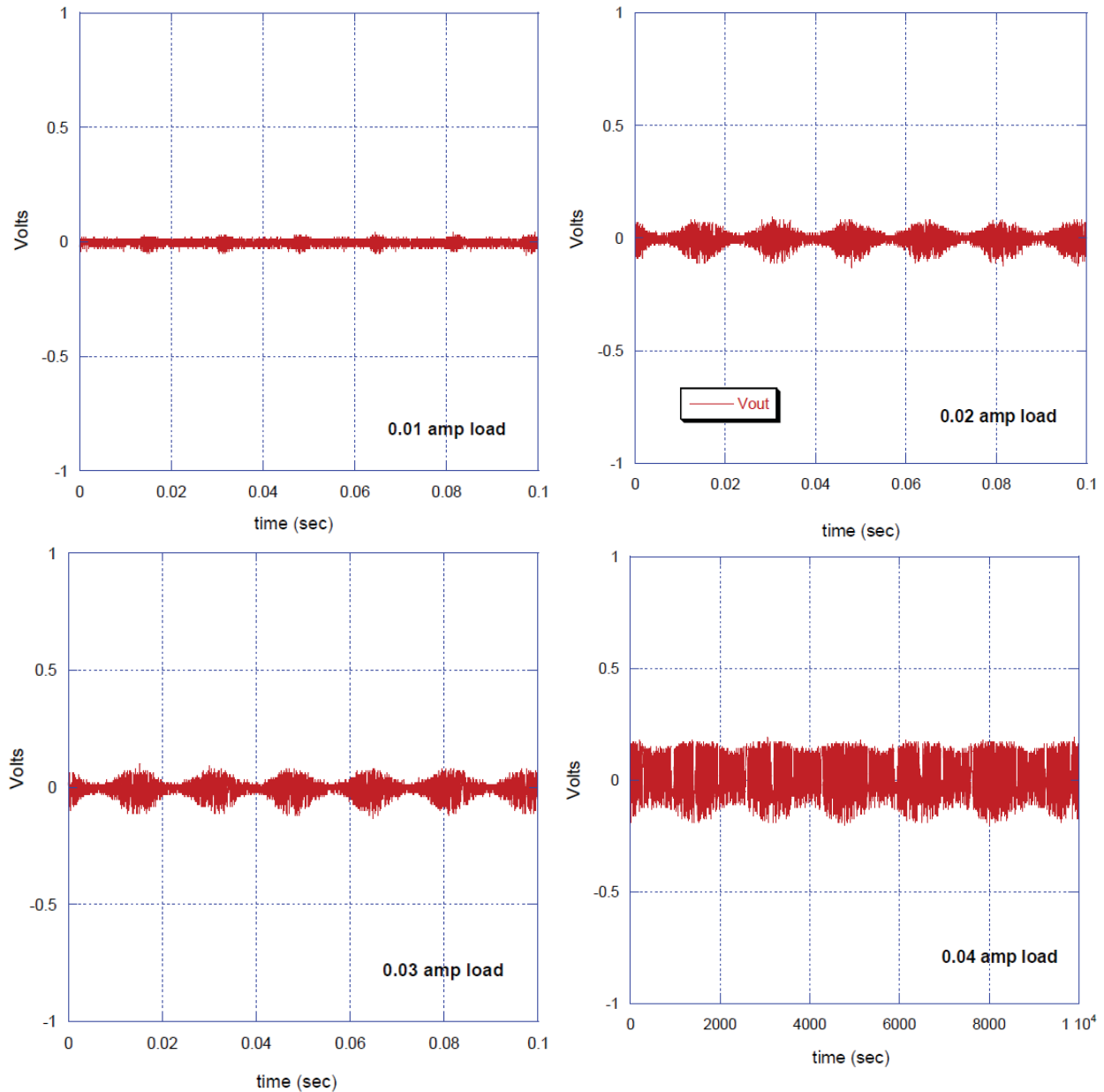


Figure 3.5-1. Ripple and noise measurement for the MSK5810RH regulator up to 20 MHz. The test was done at 2.5 V input and 1.4 V output. This figure shows progressive changes in voltage ripple and noise from 0.01, 0.02, 0.03, and 0.04 amp loads.

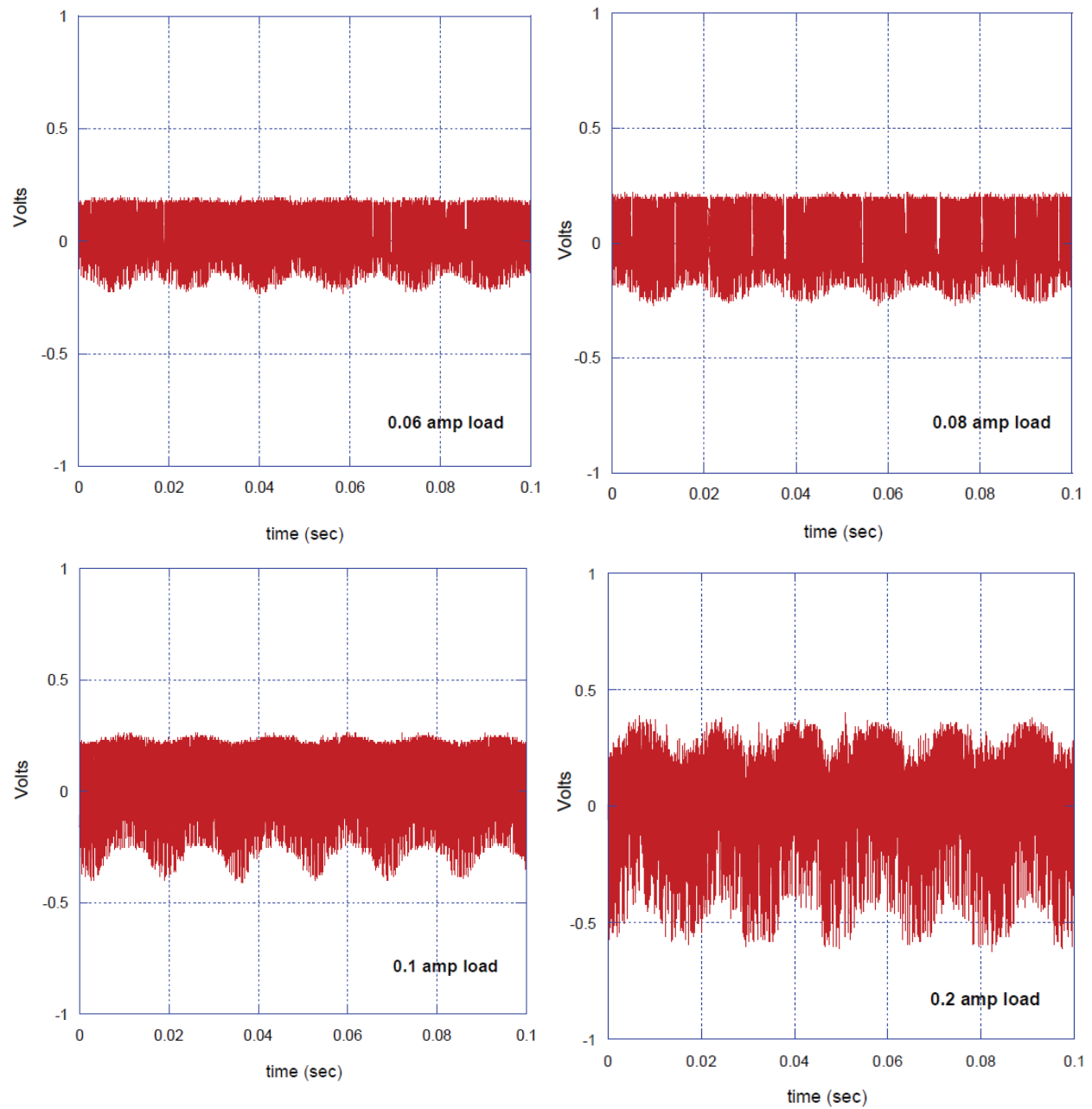


Figure 3.5-2. Ripple and noise measurement for the MSK5810RH regulator. 2.5 V input, 1.4 V output were the test conditions. This figure shows progressive changes in voltage ripple and noise from 0.06, 0.08, 0.1, and 0.2 amp.

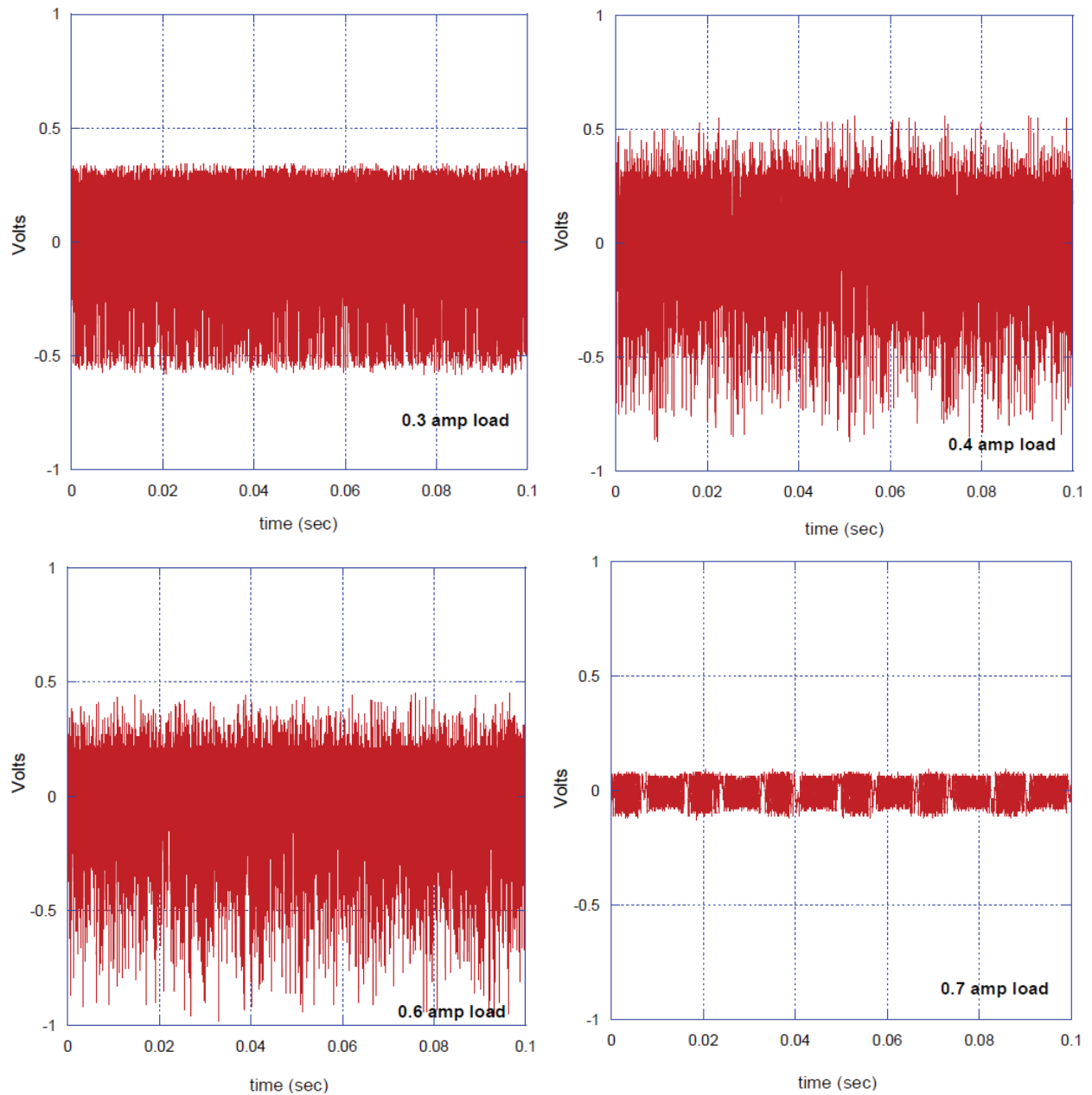


Figure 3.5-3. Ripple and noise measurement for the MSK5810RH regulator. 2.5 V input, 1.4 V output were the test conditions. This figure shows progressive changes in voltage ripple and noise from 0.3, 0.4, 0.6, and 0.7 amp.

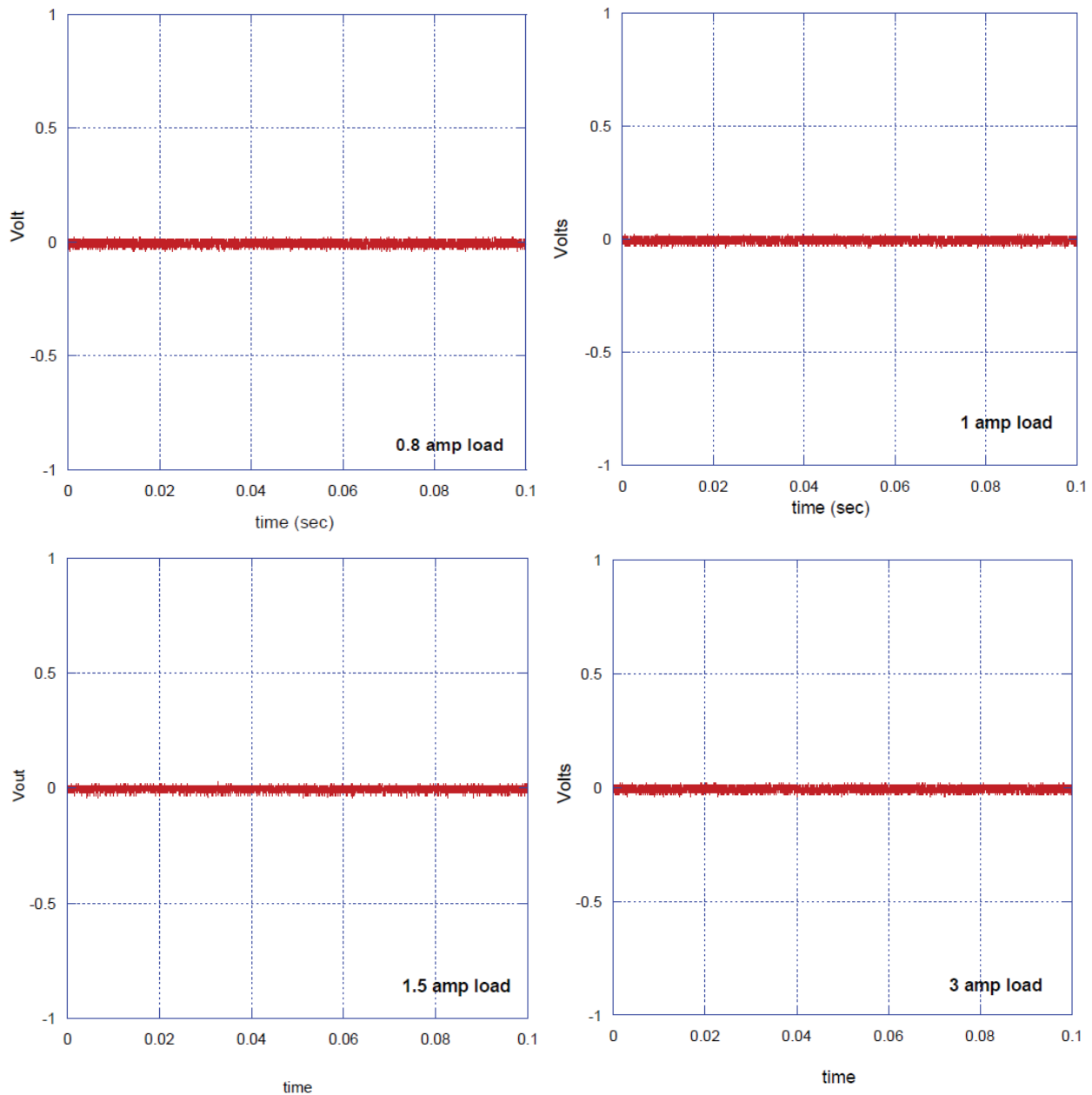


Figure 3.5-4. Ripple and noise measurement for the MSK5810RH regulator. 2.5 V input, 1.4 V output were the test conditions. Figure shows progressive changes in voltage ripple and noise from 0.8, 1.0, 1.5, and 3 amps. The voltage ripple and noise was also measured for 2 amp load, and found to be similar to the noise using 3 amp load.

As can be seen from these plots, the voltage ripple and noise are insignificant at very small loads, but rise to a significant fraction of the signal at 0.04 amp and above. The voltage ripple becomes a large fraction of the expected 1.5 V output at a large range of intermediate loads. In fact, the noise is so large at intermediate loads that it constitutes a significant fraction of the output voltage. The reasons for this unacceptably large noise at intermediate load values are still being investigated. To rule out the possibility of oscilloscope aliasing for the intermediate load values, more tests are planned in FY11 using different (shorter) timescales and a faster oscilloscope.

3.6 Operation of Point-of-Load Regulators at Their Lower Thermal Limit (-55°C and -40°C) and Below

3.6.1 Linear Regulator

The MSK5810RH linear regulator was also operated at the lower end of its specified thermal scale, -40°C . Temperature control on this device was much harder, mainly at high loads, since the thermocouple installed right at the regulator showed rapid increase in temperature. Turn-on tests and load transient response tests were performed at room temperature, and at -40°C . The device did not turn on at -40°C , and load transient response tests caused the output to become oscillatory. The thermal chamber was then raised to a higher temperature and tests were repeated for -30°C and -20°C . Normal turn on was not observed below -20°C .

Figures 3.6-1 to 3.6-5 show results of load transient response on the linear regulator while measurements were being made inside the thermal chamber. Figure 3.6-1 shows the room temperature behavior of load transient response using a step load from 1.5 A to 3 A, 3 V input and 1.7 V output. These show a lot more noise when compared with Figures 3.2-3 to 3.2-6. The reason for the increased noise is that in order to make electrical connections to and from the thermal chamber, much longer cables are needed, and therefore the noise increases. No electromagnetic interference (EMI) filter was used in these measurements.

This linear regulator device (MSK5810RH) warmed up very rapidly when oscillatory behavior was observed; therefore, at times the “real” temperature warmed to 10 or 20 degrees above the oven temperature and the regulator started functioning normally again.

Figure 3.6-2 shows the results of load transient response for the same conditions, 1.5 A to 3 A load step. The test was done with the regulator at -30°C . Figure 3.6-3 shows the same measurement done at -40°C . Figure 3.6-4 shows results from load transient response with a small load step (from 0.2 A to 2 A). As can be seen from these traces, the output voltage response can be worse for 1.5 A to 3 A load step.

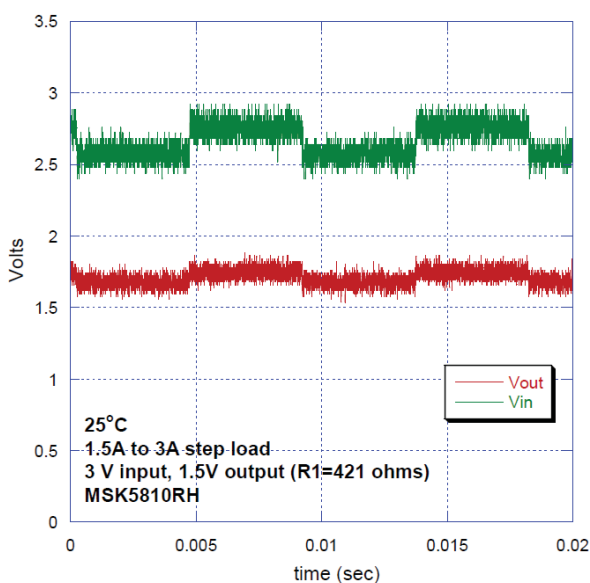


Figure 3.6-1. Load transient response test at 25°C for the linear regulator MSK5810RH. The load step was from 1.5 A to 3 A. The input voltage was 3 V and the output was 1.7 V.

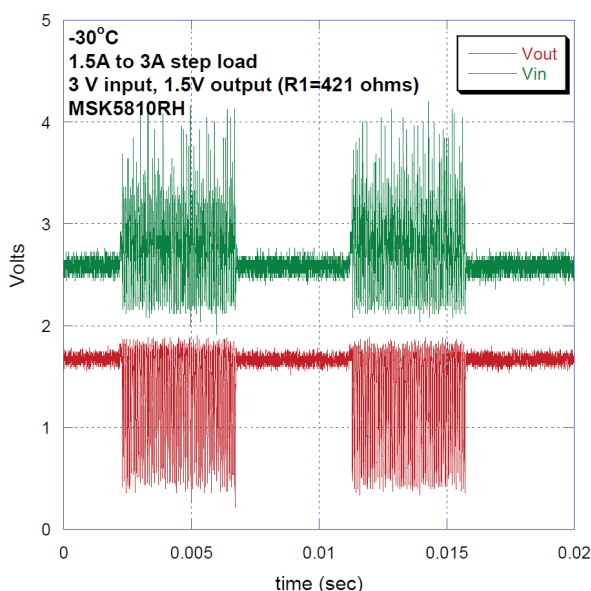


Figure 3.6-2. Load transient response test at -30°C for linear regulator MSK5810RH. The load step was from 1.5 A to 3 A. The input voltage was 3 V and the output was 1.7 V.

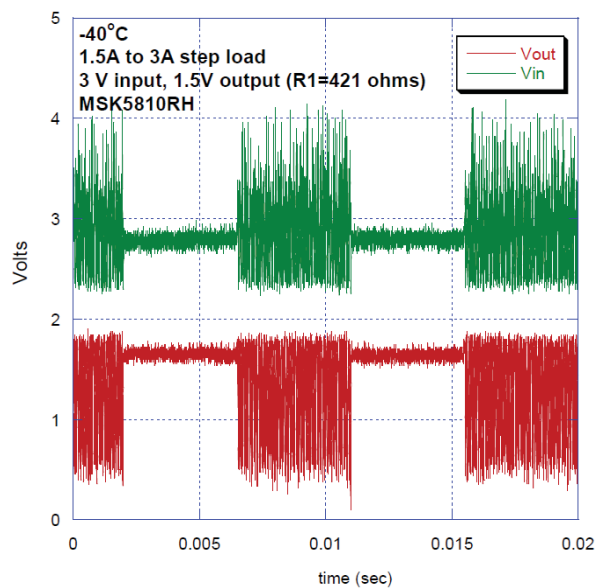


Figure 3.6-3. Load transient response test at -40°C for the linear regulator MSK5810RH. The load step was from 1.5 A to 3 A. The input voltage was 3 V and the output was 1.7 V.

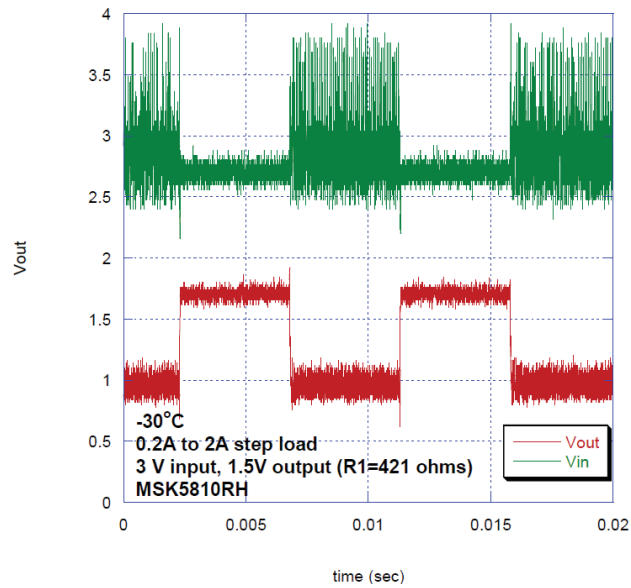


Figure 3.6-4. Load transient response test at -30°C for the linear regulator MSK5810RH. The load step was from 0.2 A to 2 A. The input voltage was 3 V and the output was 1.7 V.

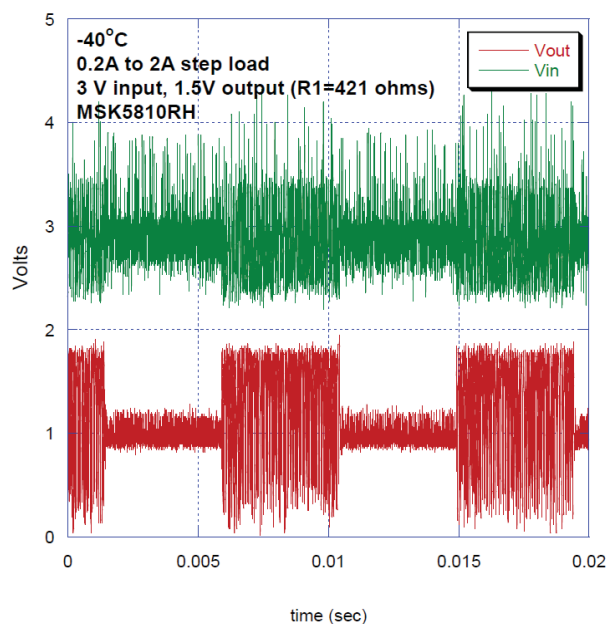


Figure 3.6-5. Load transient response test at -40°C for the linear regulator MSK5810RH. The load step was from 0.2 A to 2 A. The input voltage was 3 V and the output was 1.7 V.

Further work on the turn-on characteristics of these regulators is planned for FY11. Output capacitor values and their thermally induced changes will be examined in order to determine if these might cause the instabilities observed, or could be used to mitigate them.

3.6.2 Buck Regulator

Several features of the ISL70001SRH regulator were tested at -55°C . The turn-on characteristics as well as the load transient response was very similar to the ones measured at room temperature. Different load conditions were used just as in the room temperature measurements. Since no anomalies or even differences were found, turn-on characteristics below -55°C are presented in Appendix A (Figures A-1 to A-8).

Load transient response for ISL70001SRH regulator using 5 V input, 3.3 V output, and different step loads was done both at room temperature (but inside the thermal chamber so the connecting wire length and all other conditions other than temperature were the same) and at -55°C . The step loads used were 5% to 50% and 50% to 100% of the 6 amps maximum load. These are compared in Appendix A (Figures A-9 to A-12).

Since the performance of the ISL70001 regulator was not affected at -55°C , this regulator was cooled to an even lower temperature. Performance at very low temperature can be very helpful in the selection of commercial regulators that could be used in flight applications where cryogenic temperatures are unavoidable.

Figures 3.6-6 to 3.6-9 show results from turn-on tests with the regulator below -55°C . Figure 3.6-6 shows the lowest temperature for which we can get a normal start at the 6 amps full load. Figure 3.6-7 shows the same data for a load of 10% (0.6 amp) at -135°C . Figure 3.6-6 shows these conditions at half load, and Figure 3.6-7 shows the oscillatory behavior seen at -135°C and full load. Since the regulator can function at -135°C with less than the full load, what we see is not a temperature effect, but rather a temperature and load combined effect.

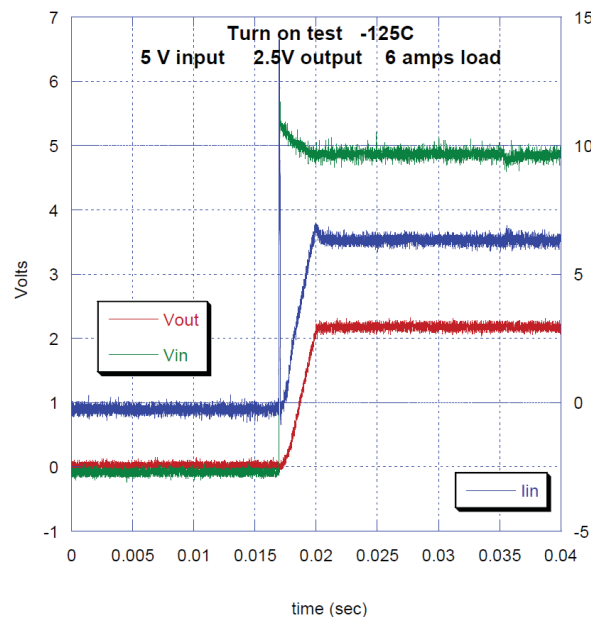


Figure 3.6-6. Turn on characteristics for the ISL70001 regulator using 5 V input and 2.5 V output and full load.

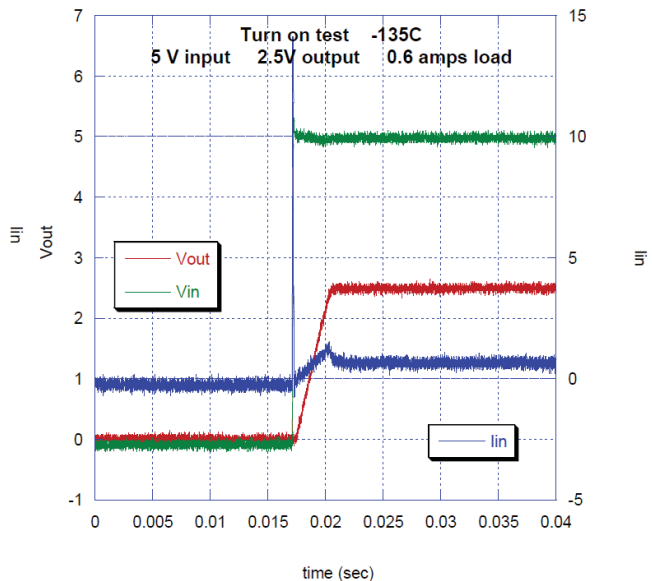


Figure 3.6-7. Turn on test for ISL70001 regulator at -135°C with 5 V input and 2.5 V output. The load was 0.6 amp, which is 10% of the maximum load.

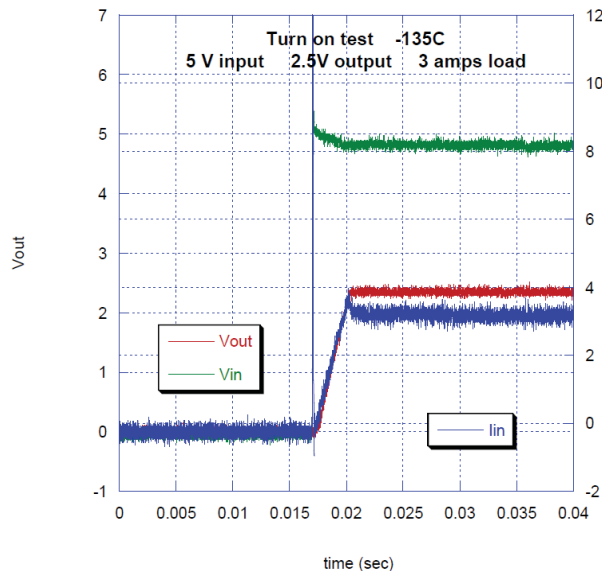


Figure 3.6-8. Turn-on test for ISL70001 regulator at -135°C with 5 V input and 2.5 V output. The load was 3 amps, which is 50% of the maximum load.

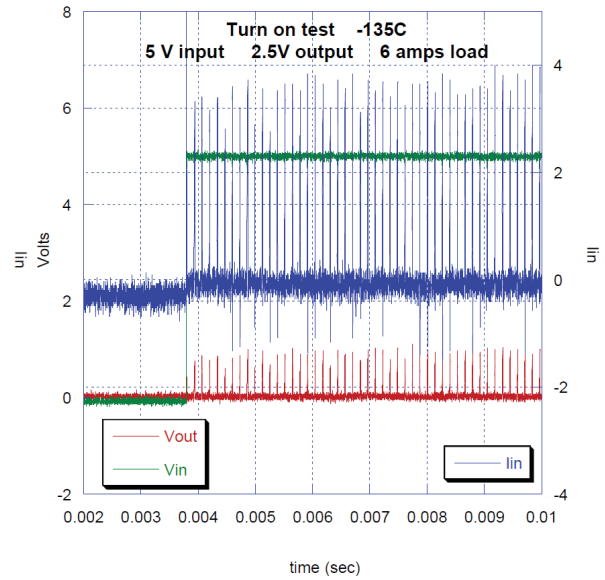


Figure 3.6-9. Turn-on test for ISL70001 regulator at -135°C with 5 V input and 2.5 V output. The load was 6 amps or a full load.

Further tests are planned for FY11 to determine the causes for the apparent instability. The regulator might oscillate due to a high Q of the input filter, or a change in the input capacitor. These tests will be repeated after changing the input capacitor value with suitable low temperatures capacitors, and perhaps changes in the input filter. These will determine if the input capacitance or input filter have an effect on the low temperature behavior of this regulator.

These low temperature results have been communicated to the manufacturer's design engineers, who have given JPL suggestions for further tests. Their guidance and recommendations in future low temperature testing of this regulator will assist JPL/NASA in determining the use parameters of these regulators. The ISL70001 shows acceptable performance down to -125°C at all loads. This is another 70°C colder than the low limit in the military scale, and this good low temperature behavior could make this regulator promising for future applications in cryogenic environments. However, understanding the limiting component and what exactly causes the regulator to oscillate is interesting. In order to gain more insight into the low temperature behavior of this regulator, the output voltage, the input current, and the reference voltage (V_{ref}) were plotted as a function of temperature. These plots are shown in Figures 3.6-10 to 3.6-12, respectively.

Figure 3.6-10 and Figure 3.6-11 show that neither output voltage nor input currents vary as much with temperature as from different load conditions. As shown in Figure 3.6-12, V_{ref} is pretty stable from room temperature down to -50°C . For low load values, it remains stable to -125°C . For the full load, the value of V_{ref} fluctuates by decreasing and then showing a sharp increase. This change in the value of V_{ref} for large load conditions might explain the converter's instability at full load below -120°C .

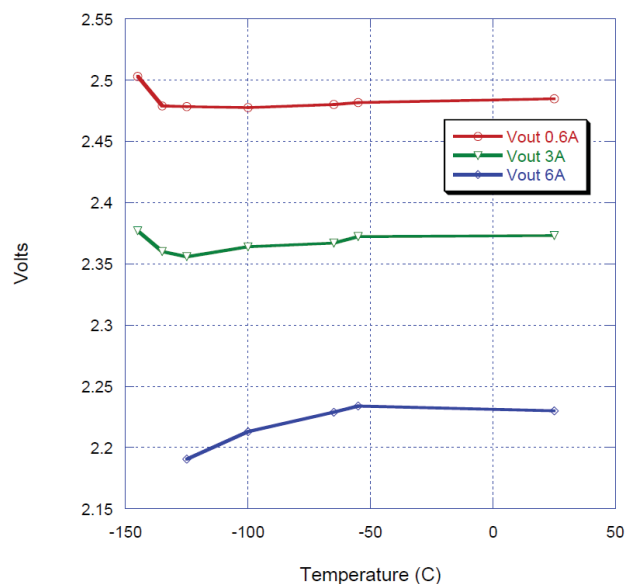


Figure 3.6-10. Voltage output for the ISL70001 buck regulator as a function of temperature.

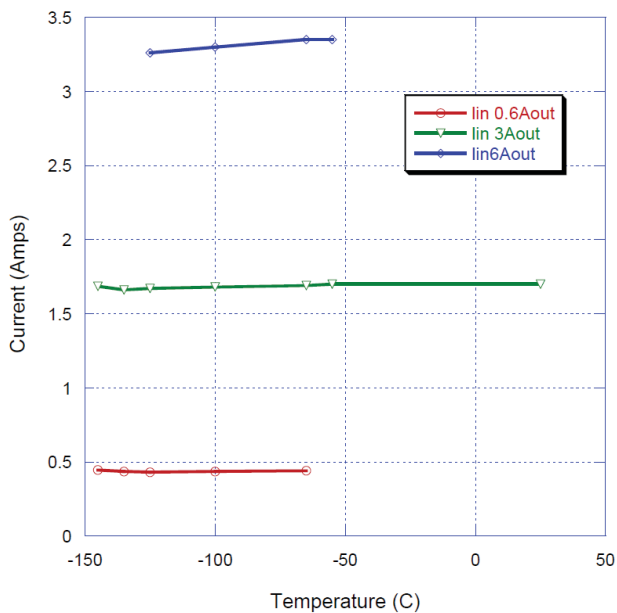


Figure 3.6-11. Current input as a function of temperature for the buck regulator ISL70001.

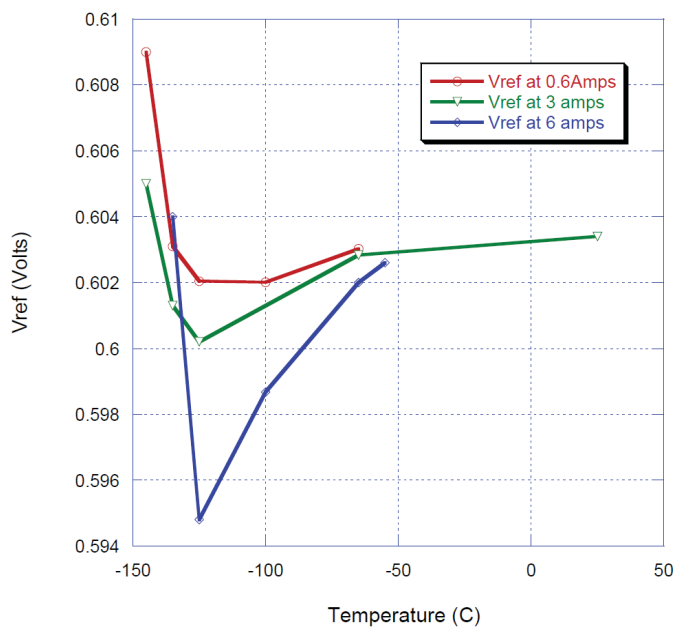


Figure 3.6-12. Value of V_{ref} as a function of temperature for the ISL70001.

4.0 SUMMARY

Tests were performed on two different types of POL regulators that have been used in past and present flight applications, and considered for future flight applications.

4.1 Summary of Findings

The synchronous buck regulator tested (ISL70001) can start at temperatures as low as -135°C as long as less than the full load is used. It will start at the full load as low as -125°C . This device performs normally at its stated lowest thermal range of -55°C . Measurements of V_{ref} indicate that low temperature operation is possible as long as less than the full load is used.

The linear POL regulator tested (MSK5810) shows an unacceptable level of voltage ripple and noise at intermediate loads.

MSK5810 will not start normally or recover from a pulsed load without oscillating if the temperature is below -20°C , even though it is rated at -40°C . Output capacitor values still need to be evaluated to determine if this will make the device stable at its lowest stated thermal range.

5.0 REFERENCES

- [1] Jin, K., M. Xu, and F. C. Lee, "Optimal Buck Converter Output Filter Design for Point-of-Load Applications," *IEEE Trans. Industrial Electron.* **57**, 1330 (2010).
- [2] Sun, J., D. Giuliano, S. Devarajan, J. Lu, T. Chow, and R. Gutmann, "Fully Monolithic Cellular Buck Converter Design for 3-D Power Delivery," *IEEE Trans. on VLSI Syst.* **17**, 447 (2009).
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- [4] Leon, R., "Report on DC/DC converter testing: ARH2812S," JPL Interoffice Memorandum 5145-08-003 (2008).
- [5] Leon, R., "Report on DC/DC converter testing: AFL2812D," JPL Interoffice Memorandum 5145-08-002 (2008).
- [6] Leon, R., "Failure modes and low temperature performance of DC/DC converters," JPL Pub. 09-36 (2009).

APPENDIX A. RESULTS FROM TURN-ON AND LOAD TRANSIENT RESPONSE AT -55°C

The following figures show results from turn-on and load transient response measurements done on synchronous buck regulator ISL70001 at -55°C .

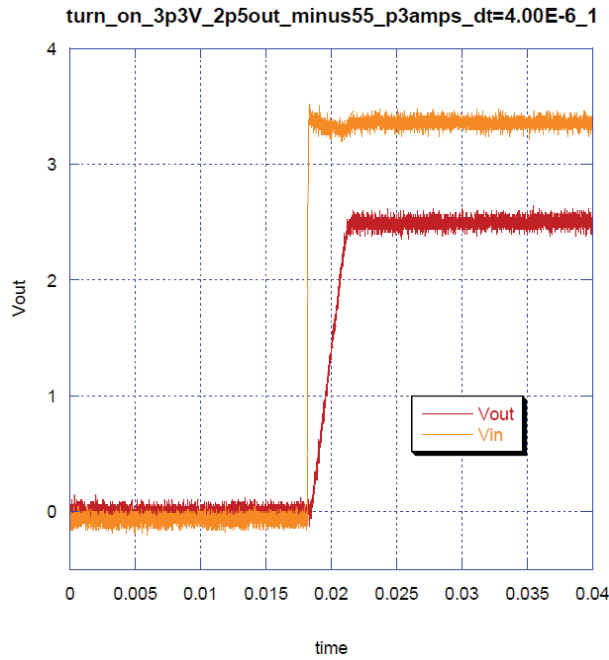


Figure A-1. Turn-on trace for ISL70001SRH regulator using 3.3 V input, 2.5 V output, and 0.3 amp load, measured at -55°C .

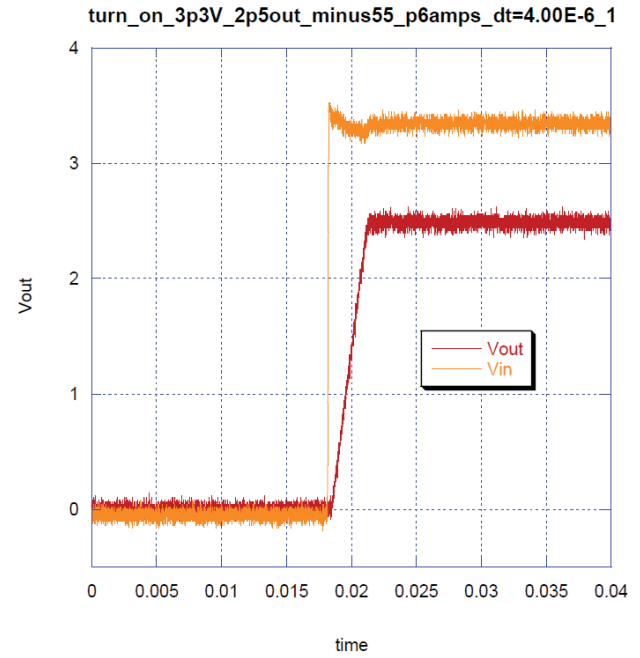


Figure A-2. Turn-on trace for ISL70001SRH regulator using 3.3 V input, 2.5 V output, and 0.3 amp load, measured at -55°C .

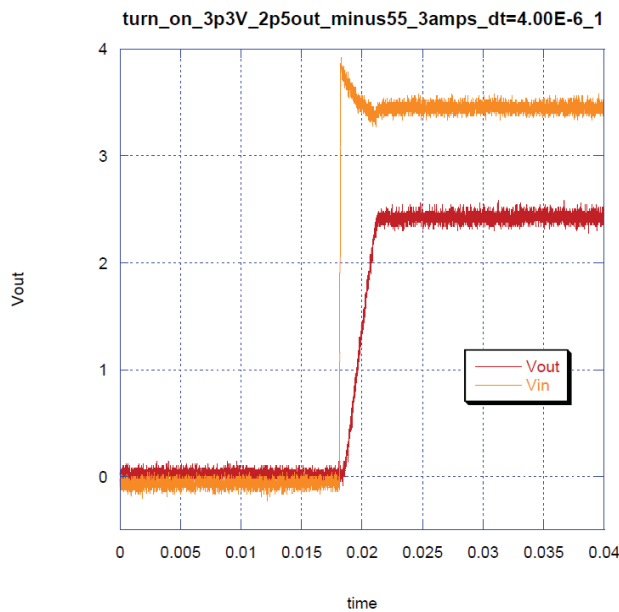


Figure A-3. Turn-on trace for ISL70001SRH regulator using 3.3 V input, 2.5 V output, and 3 amp load, measured at -55°C .

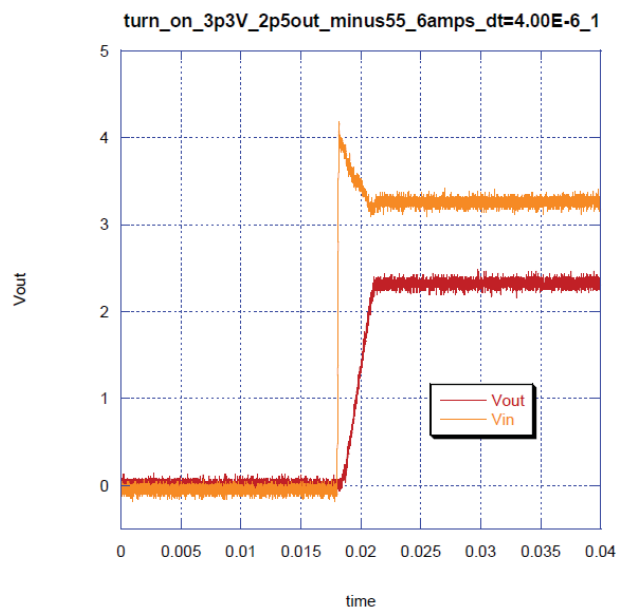


Figure A-4. Turn-on trace for ISL70001SRH regulator using 3.3 V input, 2.5 V output, and 6 amp load, measured at -55°C .

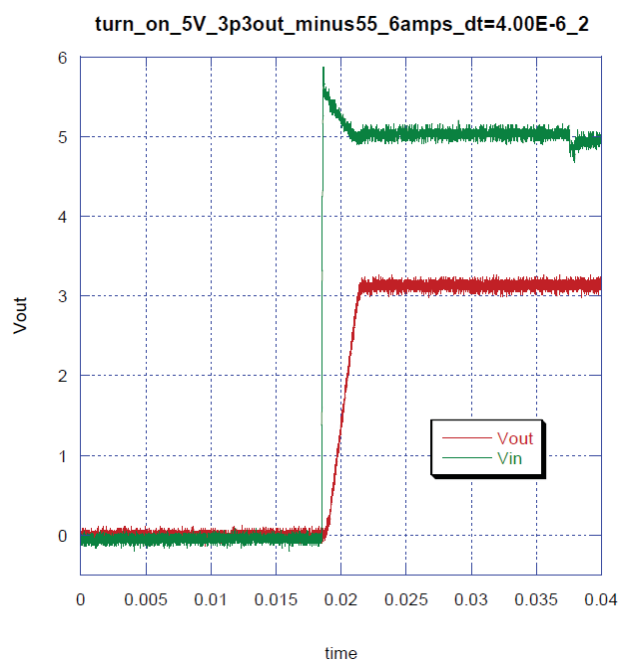


Figure A-5. Turn-on trace for ISL70001SRH regulator using 5 V input, 3.3 V output, and 6 amp load, measured at -55°C .

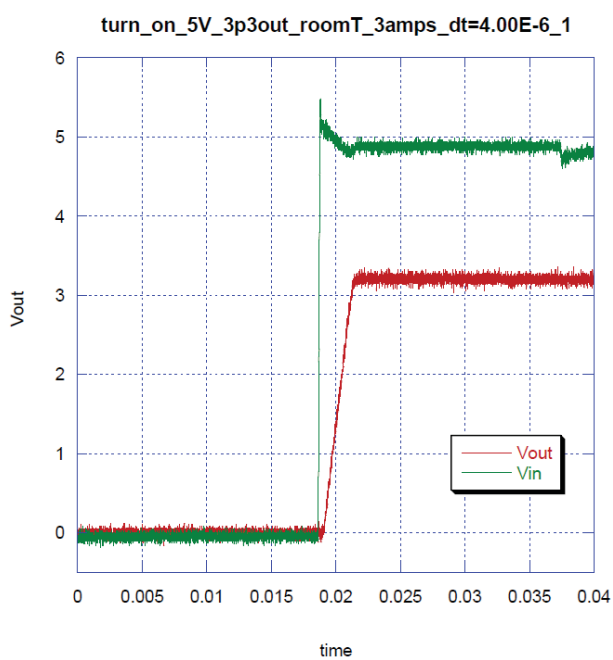


Figure A-6. Turn-on trace for ISL70001SRH regulator using 5 V input, 3.3 V output, and 3 amp load, measured at 25°C .

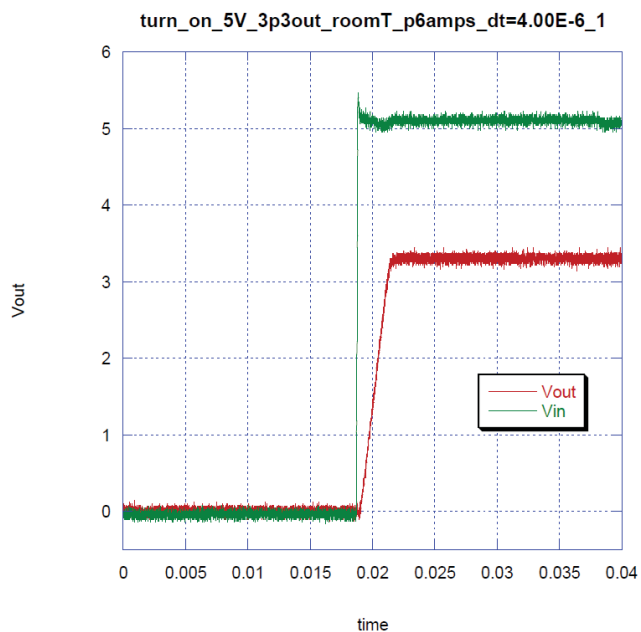


Figure A-7. Turn-on trace for ISL70001SRH regulator using 5 V input, 3.3 V output, and 0.6 amp load, measured at 25°C .

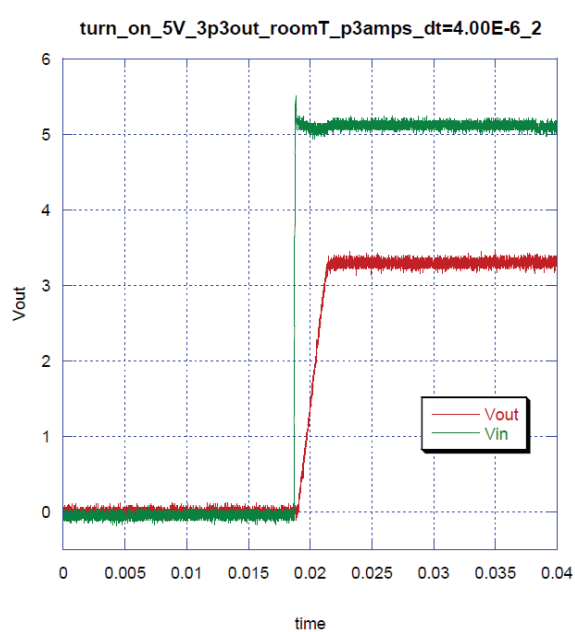


Figure A-8. Turn-on trace for ISL70001SRH regulator using 5 V input, 3.3 V output, and 0.3 amp load, measured at 25°C .

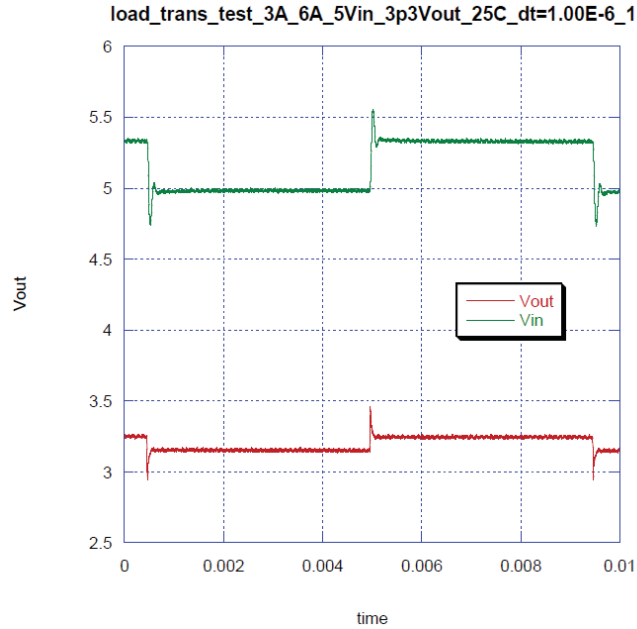


Figure A-9. Load transient response for ISL70001SRH regulator using 5 V input, 3.3 V output, and a step load of 3 to 6 amps, which in this case is half to full load. This measurement was made at room temperature (25°C) and is shown for comparison with the same conditions as the traces captures for -55°C. The regulator was inside the chamber and all cable lengths and connections were identical.

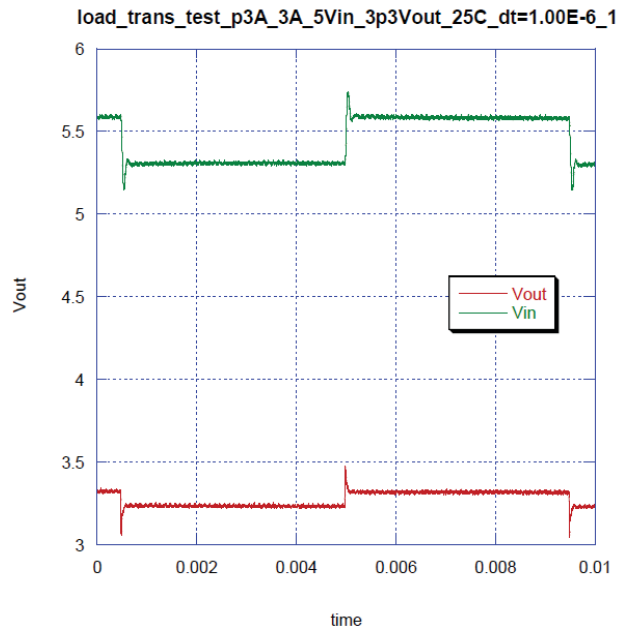


Figure A-10. Load transient response for ISL70001SRH regulator using 5 V input, 3.3 V output, and a step load of 0.3 to 3 amps, which in this case is 5% to 50% load. This measurement was made at room temperature (25°C) and is shown for comparison with the same conditions as the traces captures for -55°C. The regulator was inside the chamber and all cable lengths and connections were identical.

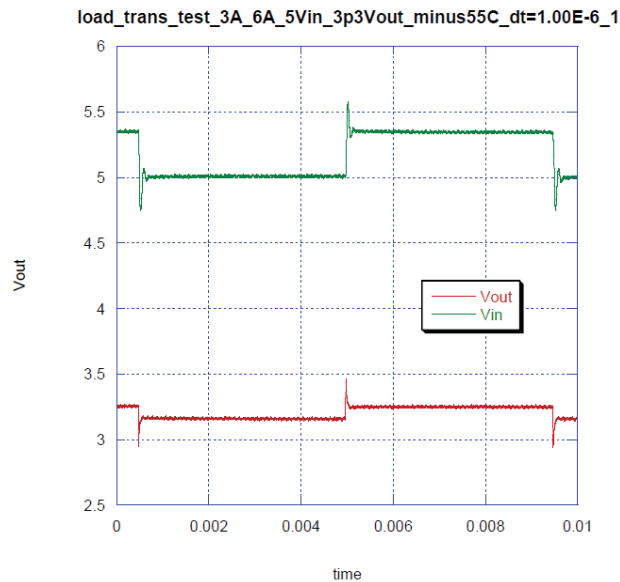


Figure A-11. Load transient response for ISL70001SRH regulator using 5 V input, 3.3 V output, and a step load of 3 to 6 amps, which in this case is 50% to 100% load. This measurement was made at -55°C, under the same conditions as the traces captures at 25°C.

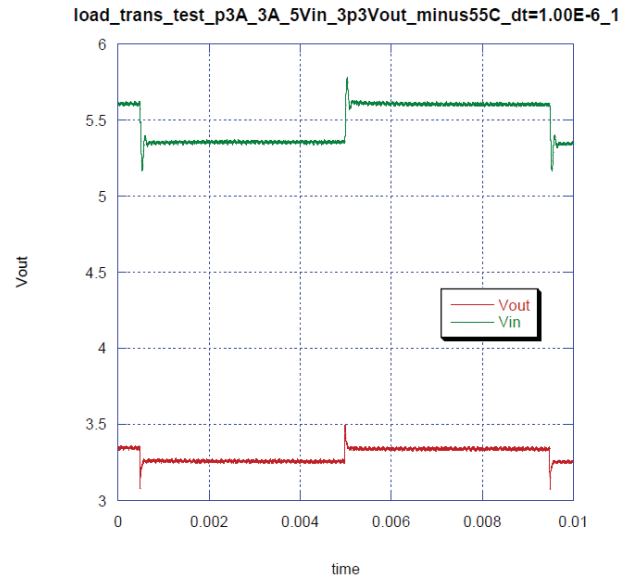


Figure A-12. Load transient response for ISL70001SRH regulator using 5 V input, 3.3 V output, and a step load of 0.3 to 3 amps, which in this case is 5% to 50% load. This measurement was made at -55°C, under the same conditions as the traces captures at 25°C.